MECHANICAL VIBRATIONS IN HYDRAULIC MACHINES

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Mechanical vibrations in hydraulic machines

Suggested vibration limits based on analysis of the IEC TK4 vibration database

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Foreword

This report is an updated version of chapter 6 in the previously published Elforsk report 12:70.

For the revision and integration of the current mechanical vibration standards for hydraulic power generating and pumping plants ISO/IEC 7919-5 and 10816-5 IEC and ISO are supporting an international workgroup (ISO/TC 108/SC 2 & IEC/TC 4 - JWG1 Vibration of Hydraulic Machines). To support the working group, analysis of the IEC TK4 vibration database has been performed by the Swedish national workgroup. The purpose of the analysis has been to form a statistical foundation for a recommendation on vibration limits in a new integrated vibration standard.

The fourth step in the total scope of work represent the additional analysis that has been performed and added to the report in this version. That corresponds to text in the report marked with greyed background. The other parts of chapter 6 in Elforsk report 12:70 are unchanged but slightly restructured in this version.

Swedish delegates in JWG1 are Åke Grahn, Vattenfall and Anders Bard, SWECO Energuide. The author of this report is Jonas Carlsson, E.ON Vattenkraft (previously SWECO Energuide). The project has been a part of Energiforsks R&D programme ”Anläggningsteknik Vattenkraft 2013-2014”. Vattenfall Vattenkraft, Fortum Generation, E.ON Vattenkraft Sverige, Statkraft Sverige, Skellefteå Kraft, Jämtkraft, Umeå Energi, Sollefteåforsens, Holmen Energi, Karlstads Energi and Jönköping Energi are participating companies in ”Anläggningsteknik Vattenkraft 2013-2014”.

Stockholm April 2015

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Summary

This report is an updated version of chapter 6 in the previously published Elforsk report 12:70. For the revision and integration of the current mechanical vibration standards for hydraulic power generating and pumping plants ISO/IEC 7919-5 and 10816-5 IEC and ISO are supporting an international workgroup (ISO/TC 108/SC 2 & IEC/TC 4 - JWG1 Vibration of Hydraulic Machines). To support the working group, analysis of the IEC TK4 vibration database has been performed by the Swedish national workgroup. The purpose of the analysis has been to form a statistical foundation for a recommendation on vibration limits in a new integrated vibration standard.

The fourth step in the total scope of work represent the additional analysis that has been performed and added to the report in this version.

As a statistical foundation for the revised standard an international vibration database have been developed. The analysis performed in this report are based on the database versions Vib_DB_ Revision_E[1], Vib_DB_Revision_F[2] and Vib_DB_Revision_J[3]. Revision E contains 2392 rows, revision F contains 2472, whereas revision J contains 7355 rows. Every row corresponds to one measurement. The database contains measurements on all types of hydraulic power generating and pumping machines and commonly more than one measurement on each machine.

During step 4 (Analyze the most recent database with methods established in earlier steps in order to propose action limits for the different machine types) of the work scope in the total project, database revision J of the database was considered. Database revision J has been improved with a vast number of measurements. The filtered database revision J was analyzed with the same method as for step 3. The median values for vibration level and shaft oscillations are presented in a table where also the suggested action limit values are presented.

The main conclusions from the previous work remain:

- No clear correlation between vibration values and the unit specific parameters such as head, rotational speed, runner diameter and radial bearing clearance can be observed which implies that both shaft oscillations and vibration velocities are relevant parameters.
- Several shortcomings can be identified for the parameter utilized dynamic bearing clearance (UDBC). High magnetic unbalance in the generator and high hydraulic unbalance in the turbine gives small shaft oscillations and small UDBC, bearing load can however be very high. A poorly aligned shaft arrangement can also give low values on shaft oscillations and UDBC, although high bearing load.
- The future standard has to distinguish at least between turbine type (Francis, Kaplan, Bulb, Pelton and Pump) and between bearing location (turbine bearing and generator bearings). Preferable is also a separation into shaft orientation (horizontal and vertical).

[1] Corresponds to Vib_DB_Revision_E-(2010-09-20)
[2] Corresponds to Vib_DB_Revision_F-(2011-11-24)
[3] Corresponds to Vib_DB_Revision_J-(2013-03-29)

- Reference values are suggested to be based on the median values, at least for turbine and generator bearings.
- Actions are suggested to be undertaken if the actual vibration value exceeds 1.6 and 2.5 times the reference value:
    - 1.6 times the reference value corresponds roughly to the 75 percentile.
    - 2.5 correspond approximately to the 90 percentiles.
- "Problem units" are evenly distributed over the complete range of measured vibration values. Surprisingly, machines labeled as "problem" in the database do not have exceptionally high vibration levels if compared to other measured values which are considered to be "normal". However, the proportion of machines marked as "problem" increases with higher vibration values. At approximately 2.5 times the median value the proportion of problem units increases more radically. This could prove that the proposed boundary levels 2.5 and 1.6 times the median value makes sense.

The suggested boundaries are significantly lower than the current boundary zones in the existing standard. The suggestion was supported by analysis that shows that the median value for the Burr-distributions is very close to the mean values for the datasets. And since the median value method objectively excludes extreme values, this method is promoted for finding the adequate reference values. The method is also verified through comparisons of the median value for a dataset with only measurements in best operating range and an unfiltered dataset. The resulting median values is nearly equal for the two compared datasets.

During 2013-2014, analysis of database revision J was also conducted. Since the number of measurements was increased with this version the aim of the analysis was to find reference values which could be used for producing action limits. These limits were produced by using the boundary levels recommended from earlier analysis and the median values calculated from the database revision J. The recommended action limits from this analysis is generally at the same level as calculated from previous revisions of the database. Exceptions are shaft oscillations for Bulb units which results in increased values compared to previous database revisions.

Suggested future work:

- Verify the suggested action limits with more or improved data if the database is revised.
- Refine the "problem" definition in the database.
- Identify relevant bearing groups from the database for parameter correlation.
- Identify the relationship between the vibrations of the generator guide bearings and the turbine guide bearing.
- Explain the measured shaft movements that is larger than the specified available bearing clearance.
- It is also suggested to identify the impact of the current requirements of IEC/ISO of 30 µm p-p for stationary parts. Current ISO 10816-5 action limits of 30 µm p-p is more severe for the majority of large-scale turbines than the future recommended limits that will be expressed in mm/s.

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1 Introduction

1.1 INTERNATIONAL WORKGROUP ISO/TC 108/SC 2 & IEC/TC 4 - JWG1 VIBRATION OF HYDRAULIC MACHINES

For the revision and integration of the current mechanical vibration standards for hydraulic power generating and pumping plants ISO/IEC 7919-5 and 10816-5 IEC and ISO are supporting an international workgroup (ISO/TC 108/SC 2 & IEC/TC 4 - JWG1 Vibration of Hydraulic Machines).

Swedish delegates in the international workgroup are Åke Grahn and Anders Bard and a Swedish working group has been formed for dealing with this topic.

1.2 SCOPE OF WORK

To support the international working group ISO/TC 108/SC 2 & IEC/TC 4 - JWG1 analysis of the updated TK4 vibration database has been performed by the Swedish working group.

The purpose of the analysis has been to form a statistical foundation for a recommendation on vibration limits in a new integrated vibration standard.

Earlier revisions of the database have been evaluated through a master thesis by Junnosuke Oguma performed at Luleå University of Technology in 2009, and pervious project work at SWECO. A number of shortages were highlighted and no correlation between measured values and dangerous vibration levels could be found. For stationary parts, no analyses were made due to lack of measurement data in the database. Present database has been expanded which proposes further study of the database.

This report describes the analysis work carried out by the Swedish national workgroup and the preliminary results this has led to. The work has been conducted in four steps:

1. Establish an assessment for the validity of the current database to see if data was improved.
2. Analyze the database versus a number of different parameters in order to find correlations and physical explanations on the findings.
3. Analyze an unfiltered and more recent version of the database.
4. Analyze the most recent database with methods established in earlier steps in order to propose action limits for the different machine types.

2 Analyzing method

2.1 DATABASE

As a statistical foundation for the revised standard an international vibration database have been developed. The analysis performed in this report are based on the database versions Vib_DB_ Revision_E[4], Vib_DB_Revision_F[5] and Vib_DB_Revision_J[6]. Revision E contains 2392 rows, revision F contains 2472, whereas revision J contains 7355 rows. Every row corresponds to one measurement. The database contains measurements on all types of hydraulic power generating and pumping machines and commonly more than one measurement on each machine.

2.2 FILTERNING OF DATA AND ASSESSMENT OF THE VALIDITY OF THE CURRENT DATABASE

During step 1 and 2 of the work scope in this project, revision E of the database was considered. The database contains numerous machines with more than one measurement. In order for the statistics to be comparable each machine must be given equal weight. Because of this the database has been filtered so that only one measurement per machine remains. The most excluding filtering condition was that rows not containing both bearing vibrations and shaft oscillations were removed. The remaining measurements are chosen in order that it only contains vertical machines of the type Kaplan and Francis, for the type Bulb also horizontal machines are included. For the parameter "relative output at measurement" all measurements outside the interval below were excluded.

- Francis: 70-100%
- Kaplan: 50-100%
- Bulb: 0-100%

It was desirable to use measurements done close to the operation point at maximum efficiency. Due to lack of relative flow data, this operation point was not possible to define for all measurements. The parameter "ISO machine group" was considered and for the types Kaplan and Francis, measurements with value 1 and 2 were filtered out. For Bulb no filtration of this parameter was done. Table 1 below shows the number of remaining measurements after filtration.

Type	Generator guide bearing non drive end				Generator guide bearing drive end				Turbine guide bearing			
	Shaft		Bearing		Shaft		Bearing		Shaft		Bearing	
	Smax	Sp-p	Sp-p	VRMS	Smax	Sp-p	Sp-p	VRMS	Smax	Sp-p	Sp-p	VRMS
Bulb	5	3	3	7	5	2	4	7	9	2	4	6
Francis	146	37	9	114	142	26	7	106	146	65	12	138
Kaplan	41	20	3	36	43	15	2	33	46	32	7	46

Table 1: Number of existing measurements after filtration of database revision E

[4] Corresponds to Vib_DB_Revision_E-(2010-09-20)
[5] Corresponds to Vib_DB_Revision_F-(2011-11-24)
[6] Corresponds to Vib_DB_Revision_J-(2013-03-29)

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As can be seen from Table 1 only a fraction of the measured data remains after the filtration. Earlier reports concluded that few measurements included vibration data on both rotating and stationary parts. With revision E this has been improved, see table 2 below.

Type	Generator guide bearing non drive end		Generator guide bearing drive end		Turbine guide bearing	
	Spp or Smax + bearing housing vibration displacement	Spp or Smax + bearing housing vibration velocity	Spp or Smax + bearing housing vibration displacement	Spp or Smax + bearing housing vibration velocity	Spp or Smax + bearing housing vibration displacement	Spp or Smax + bearing housing vibration velocity
Bulb	2	3	1	5	4	5
Francis	7	100	5	92	10	114
Kaplan	0	25	0	25	4	34

Table 2: Number of measurements on both rotating and stationary parts in database revision E

Although the database has been improved, still it suffers from inconsistency. For this reason the data set varies depending on the chosen parameter.

In the database revision F all data was considered during the analysis. For consistency a separation between machine types and shaft orientation was done. Also, units marked as “problem” was analyzed separately. Francis-, Kaplan- and Pump-units which had undefined shaft orientation was assumed to be vertical if the runner diameter exceeded 2 m. Bulb-units which had undefined shaft orientations was assumed to be horizontal if the runner diameter exceeded 2 m.

Table 3 below summarizes the separation of data.

Type	Shaft orientation	Total number	Problem units
Pelton	horizontal	73	14
	vertical	67	4
	undefined	5	0
	total	**145**	**18**
Francis	horizontal	161	7
	vertical	1219	129
	undefined	45	31
	total	**1425**	**167**
Kaplan	horizontal	10	4
	vertical	361	23
	undefined	2	0
	total	**373**	**27**
Pump	Horizontal	39	0
	vertical	361	41
	undefined	9	18
	total	**409**	**59**
Bulb	horizontal	50	0
	vertical	1	0
	undefined	0	0
	total	**51**	**0**
Other	**total**	**69**	**3**
Total		**2472**	**274**

Table 3: Number of measurements separated in turbine types, shaft orientation and problem units

During step 4 of the work scope in this project, database revision J of the database was considered. Database revision J has been improved with a vast number of measurements. The majority of data originates from Chinese measurements. Since numerous of the Chinese measurements are conducted on only a few units the data have been filtered according to the following method. Analysis of the database included all measurements but with Chinese data reduced so that only maximum three measurements per unit are included. Selection of measurements in the normal operating range is prioritized and measurements marked as problem are excluded.

2.3 ANALYZING METHOD

2.3.1 Step 1 and 2

For step 1 (Establish an assessment for the validity of the current database to see if data was improved) and 2 (Analyze the database versus a number of different parameters in order to find correlations and physical explanations on the findings) of the work scope database revision E was analyzed. Each data set was plotted in diagrams with different parameters and vibration values. Due to the scattered data no clear trends were observed. A curve fitting method based on the median values was then adopted. The data was separated into smaller groups with the same numbers of data. For each group the median values was calculated for abscissa and ordinate and then projected onto the diagrams with the scattered source data. With this method extreme values are objectively excluded and do not influence any assumed trend.

Also an attempt in finding the statistical distribution function of the vibration data has been done. This was mainly done by software routines producing the best fit for each data set. Each parameter analysis is made on each machine type, Kaplan and Francis. For Bulb, no analysis was done since the available data set was considered too small. Bearing location have been considered and also the arrangement of generator bearings.

2.3.2 Step 3

For step 3 (Analyze an unfiltered and more resent version of the database) of the work scope in this project database revision F was analyzed. For the analysis the median value was calculated for the groups defined in table 3. The different bearing locations was considered and also if the measurements was marked as "problem" in the database. The median values for the individual groups were then plotted in bar charts for visualization of vibration levels. In addition, the median values from the filtered database revision E for vertical Francis and Kaplan units was projected on the corresponding charts for revision F. This for comparison with revision F. The distribution of measured values has also been plotted and projected on the proportion of units marked as "problem".

2.3.3 Step 4

For step 4 (Analyze the most recent database with methods established in earlier steps in order to propose action limits for the different machine types) the filtered database revision J was analyzed with the same method as for step 3. The median values are presented in a table where also the action limit values are presented.

3 Analysis

3.1 ANALYZE THE DATABASE VERSUS A NUMBER OF DIFFERENT PARAMETERS IN ORDER TO FIND CORRELATIONS AND PHYSICAL EXPLANATIONS ON THE FINDINGS

A number of parameters have been evaluated for database revision E in order to find correlation of vibration levels. The parameters considered are:

- Head
- Nominal speed
- Runner diameter
- Radial bearing clearance
- All plots are presented below and also in appendix1.

3.1.1 Head

The utilized dynamic bearing clearance (UDBC) shows no or small tendency of relation to increasing head. The turbine guide bearing (TGB) in Francis machines shows an increasing tendency with increasing head. All other bearings show no correlation between UDBC and head. See figure 1 and 2.

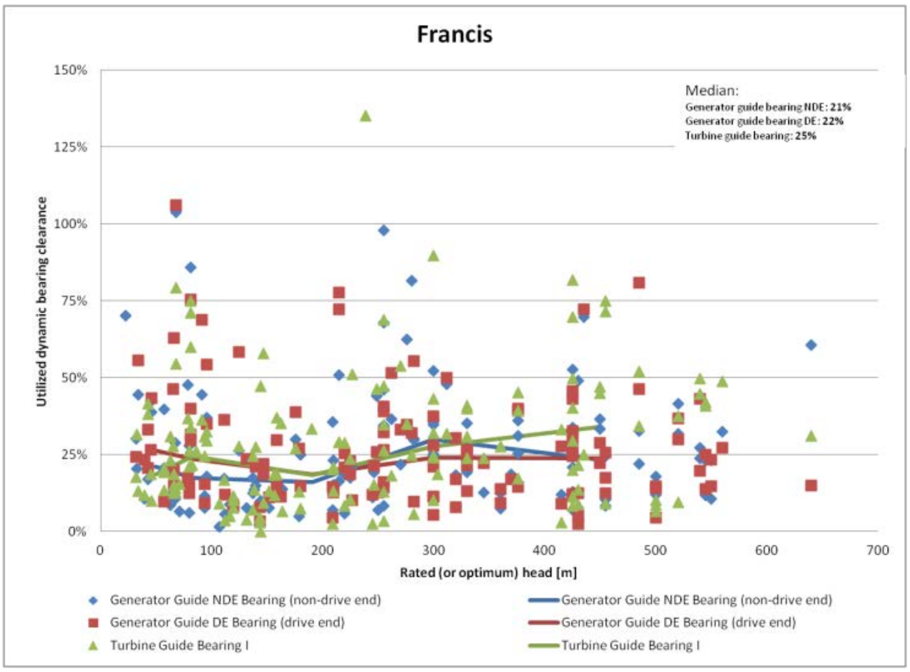


Figure 1: UDBC vs. Rated head for Francis

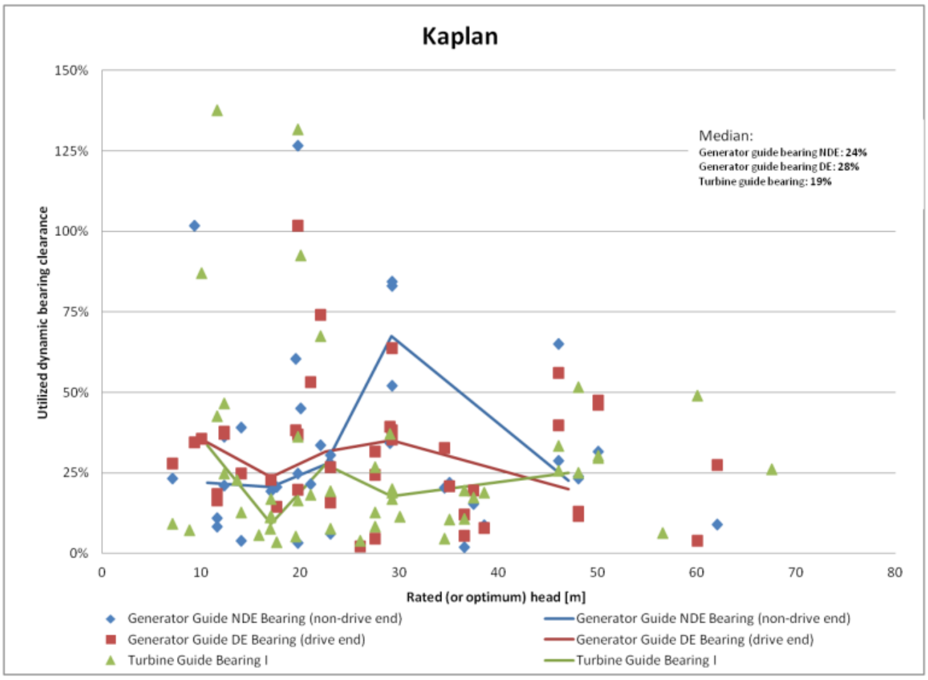


Figure 2: UDBC vs. Rated head for Kaplan

The shaft vibration displacement peak-to-peak value (Spp) shows no correlation to head. For Kaplan units the data is very scattered and the fitted median curve fluctuates heavily. See figure 3 and 4.

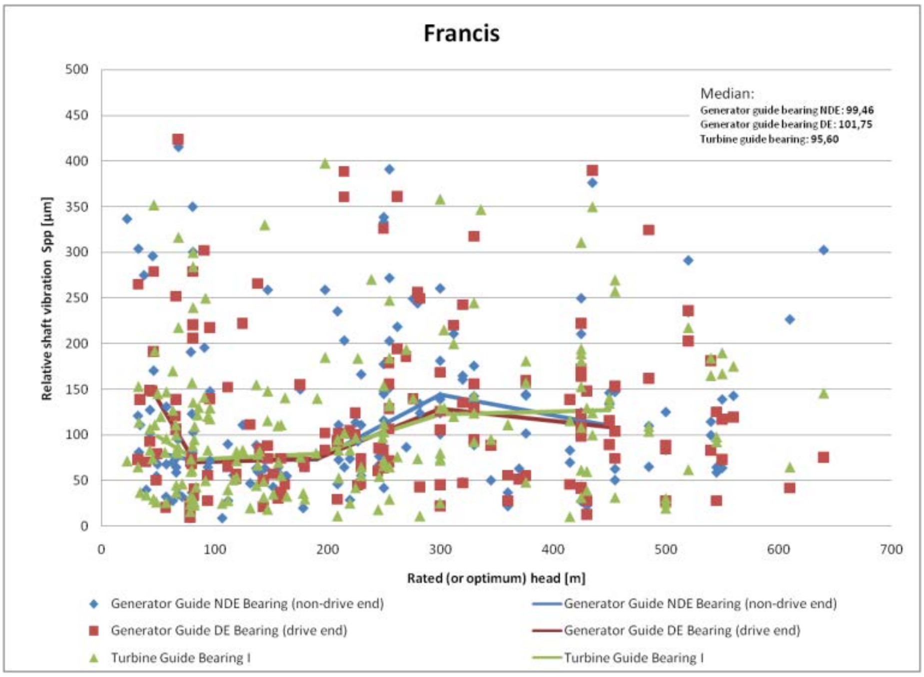


Figure 3: S_{pp} vs. Rated head for Francis

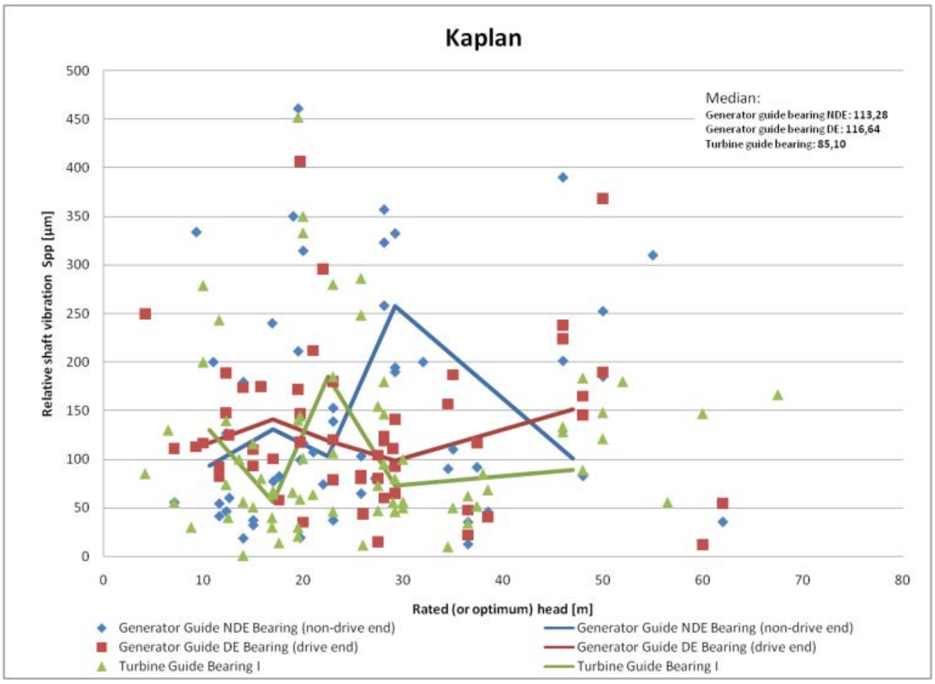


Figure 4: S_{pp} vs. Rated head for Kaplan

The bearing housing vibration velocity shows a small increase with higher heads. This trend is most apparent for The turbine guide bearing (TGB) in Kaplan units. See figure 5 and 6.

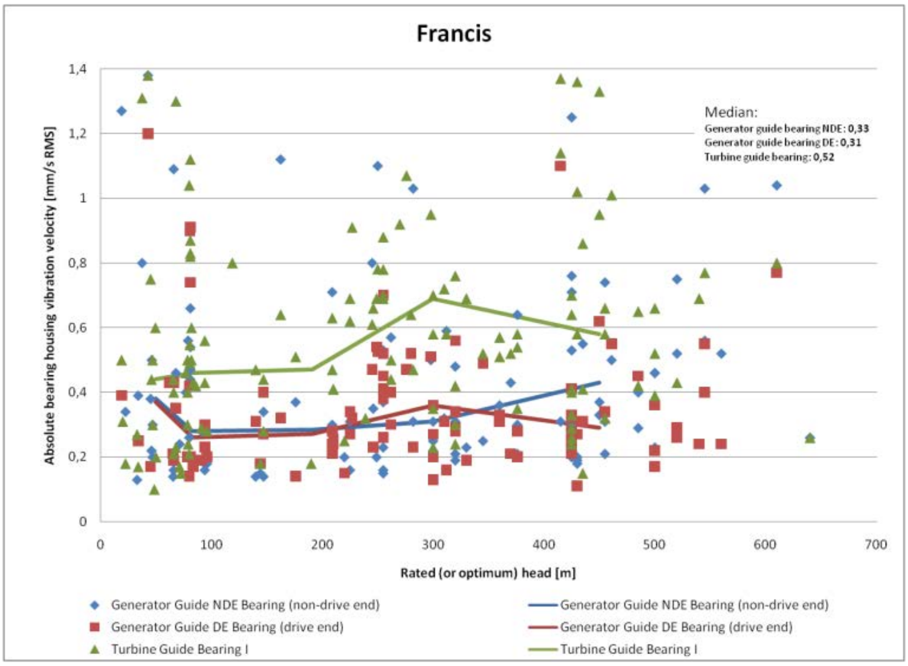


Figure 5: Vibration velocity vs. Rated head for Francis

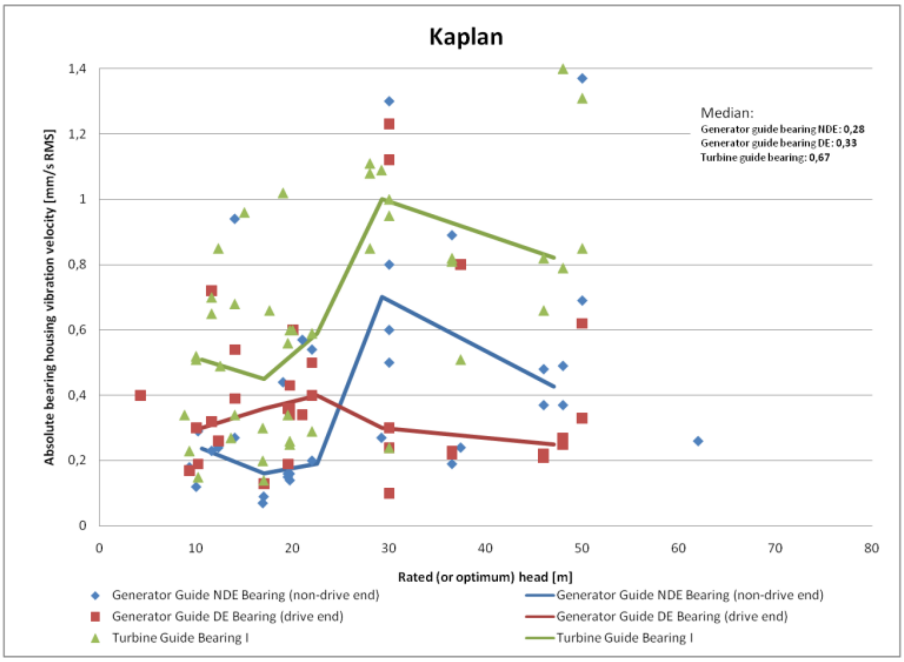


Figure 6: Vibration velocity vs. Rated head for Kaplan

No clear correlation between vibration values and head can be identified. However, for The turbine guide bearing (TGB), an increase in vibration velocities can be observed for higher heads, no or weak influence can be observed for generator guide bearing (GGB). This is valid for both turbine types. For Francis turbines a small increase in vibration level are found for heads above 200 meters.

3.1.2 Runner nominal speed

The utilized dynamic bearing clearance (UDBC) has a somewhat increasing trend for turbine guide bearing (TGB) in Francis units at increasing speed. A similar but weaker trend is present for generator guide bearing (GGB) in Kaplan units. Beyond these two, no relation between UDBC and nominal speed can be found, see figure 7 and 8.

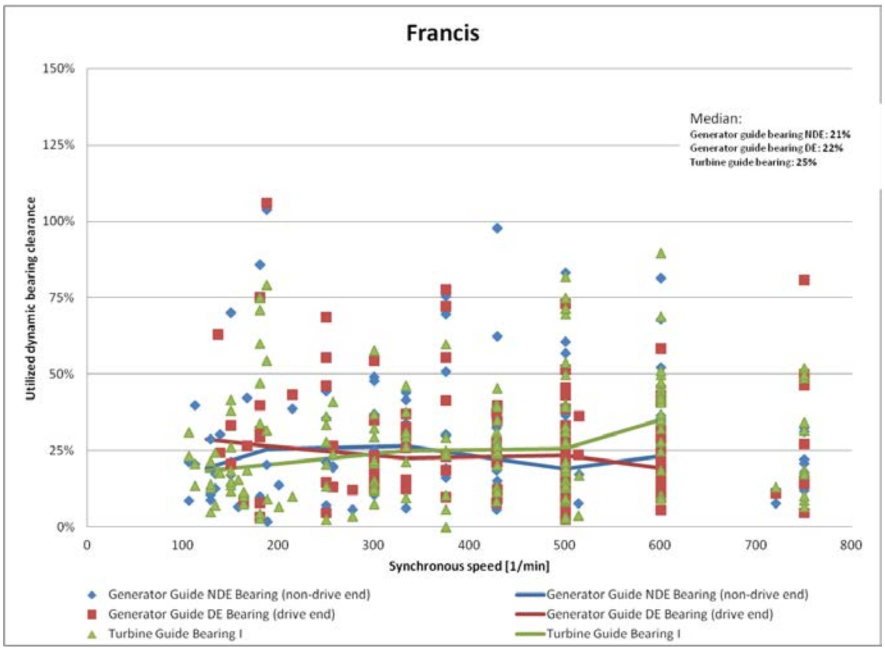


Figure 7: UDBC vs. Sync. speed for Francis

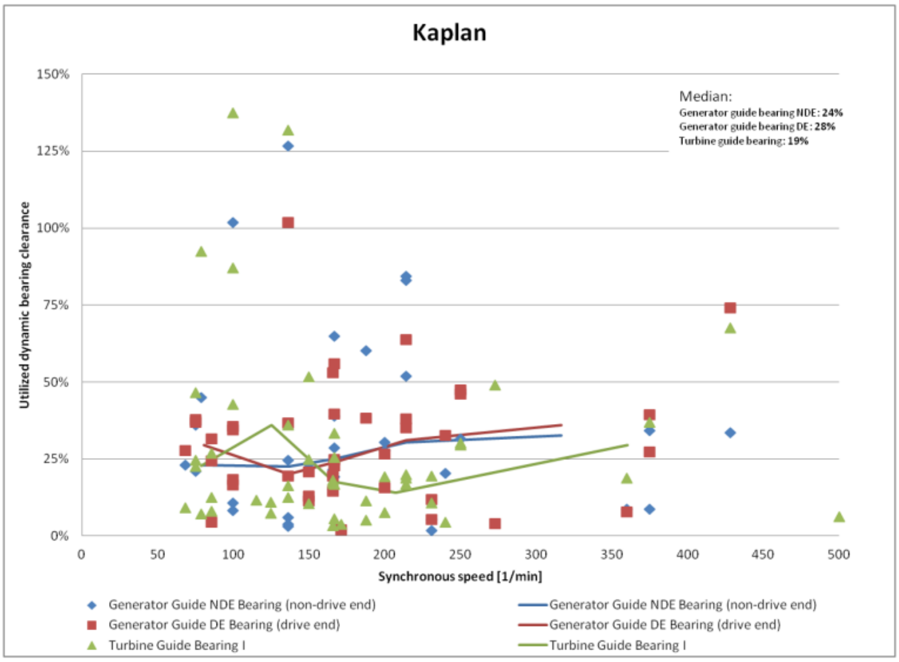


Figure 8: UDBC vs. Sync. speed for Kaplan

No relation between shaft vibration displacement peak-to-peak (Spp) and nominal speed could be found. Measurement data for both Francis and Kaplan is very scattered and the fitted median curve fluctuates between 50 and 150µm for the whole speed range, see figure 9 and 10.

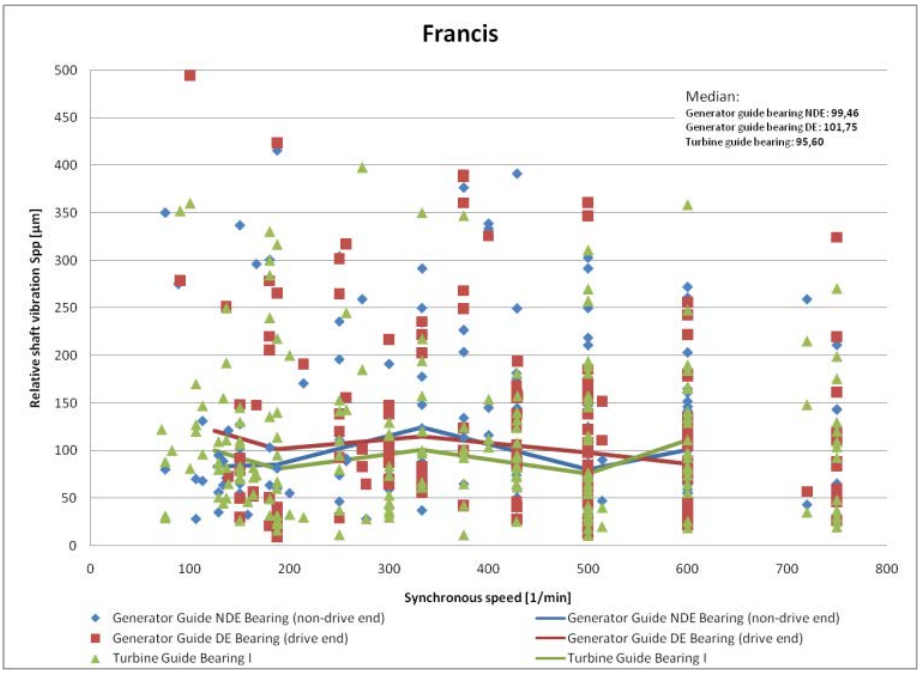


Figure 9: S_{pp} vs. Sync. Speed for Francis

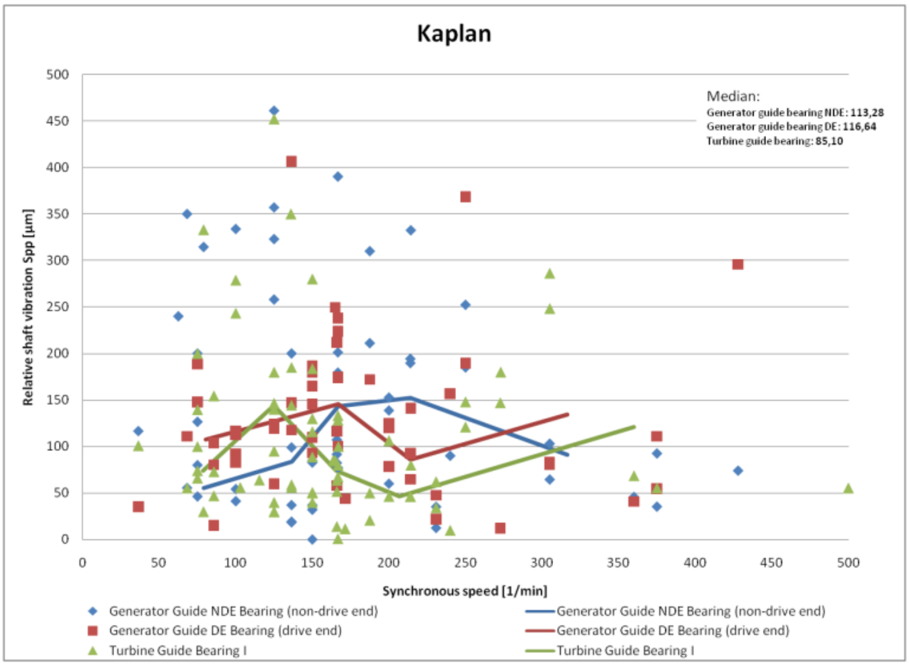


Figure 10: S_{pp} vs. Sync. speed for Kaplan

For turbine guide bearing (TGB) the bearing housing vibration velocity is clearly increasing with higher nominal speed in both turbine types. For GGB no clear trend is shown, see figure 11 and 12.

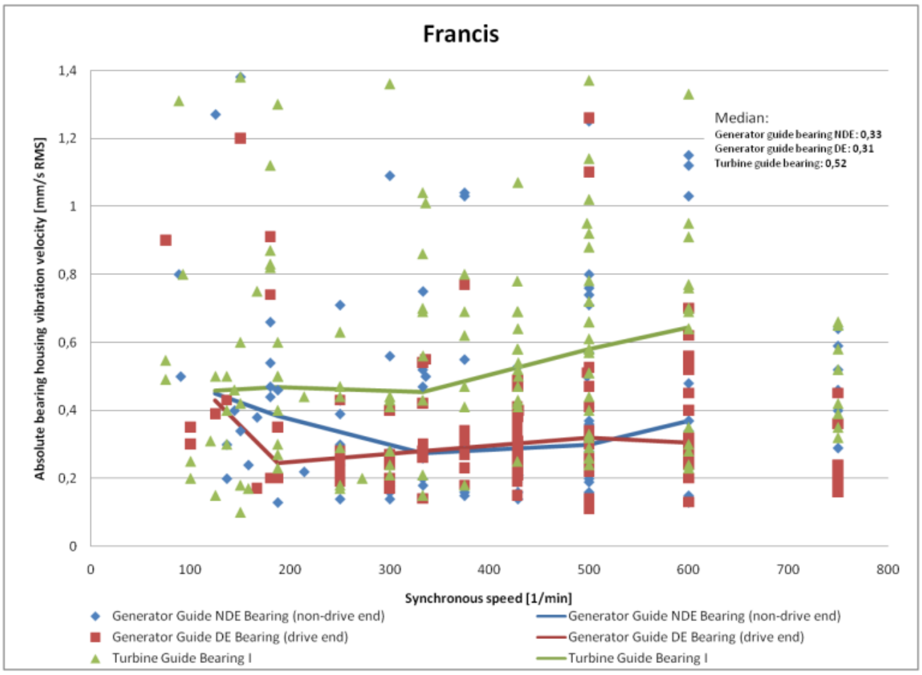


Figure 11: Vibration velocity vs. Sync. Speed for Francis

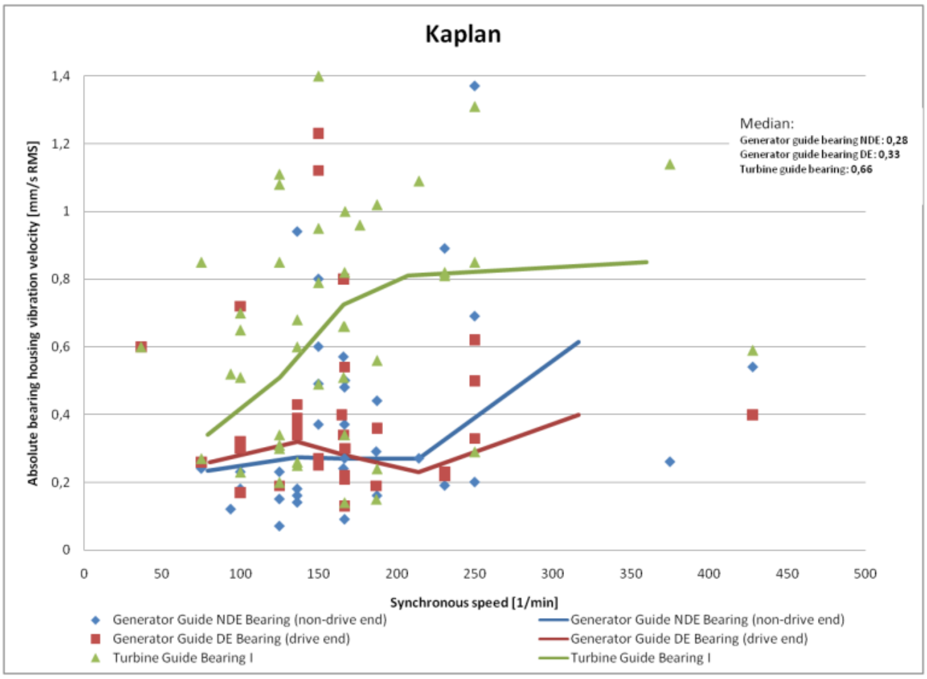


Figure 12: Vibration velocity vs. Sync. speed

No clear correlation between vibration values and nominal speed could be observed. For turbine guide bearing correlation between vibration velocity and speed can be identified.

3.1.3 Runner diameter

The utilized dynamic bearing clearance (UDBC) shows no clear trend for increasing diameter. The turbine guide bearing in Francis units shows decreasing UDBC with increasing runner diameter, this cannot be observed for the Kaplan turbine or for generator guide bearings. See figure 13 and 14.

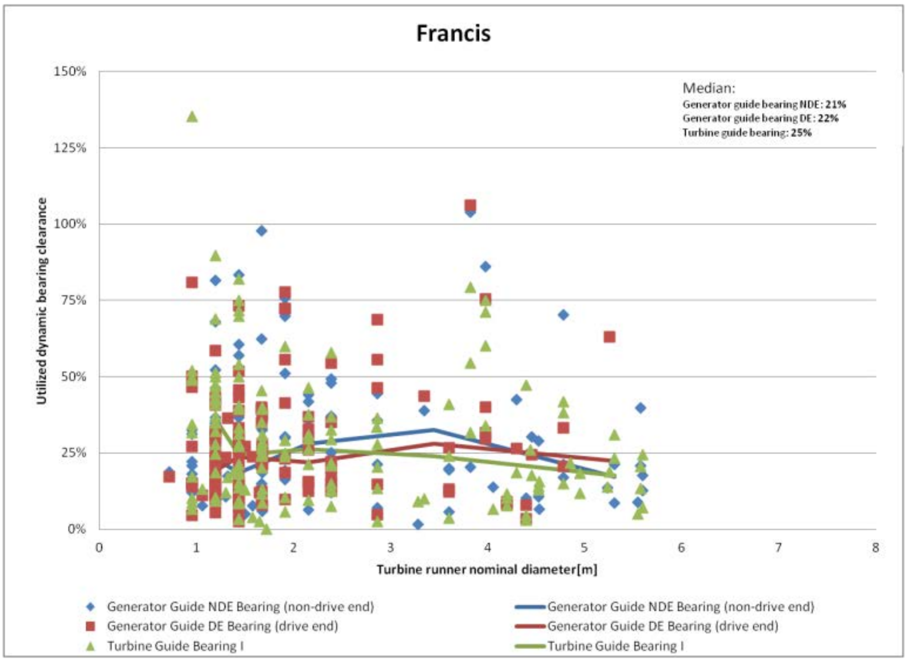


Figure 13: UDBC vs. Nominal diameter for Francis

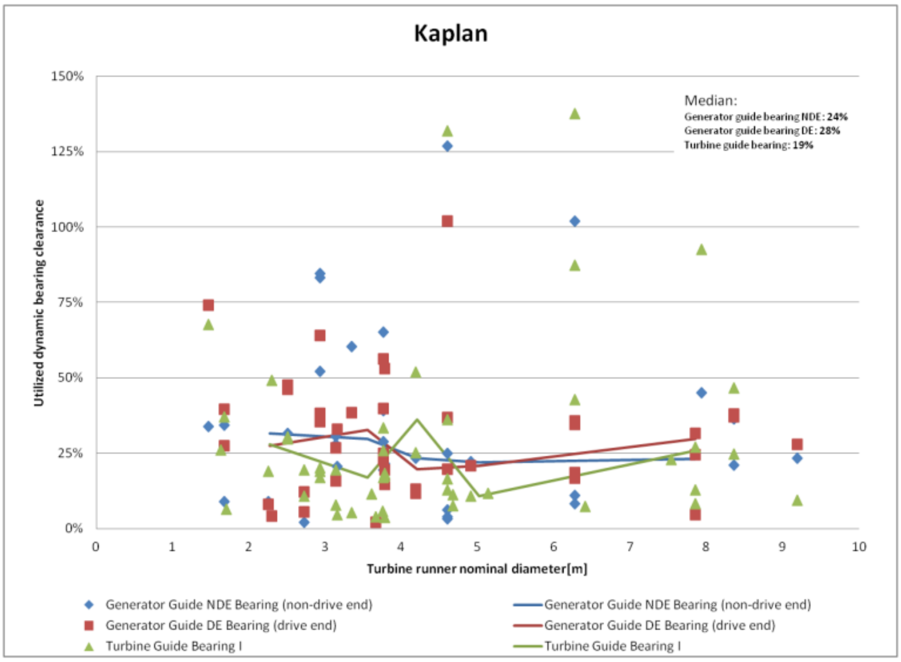


Figure 14: UDBC vs. Nominal diameter Kaplan

No relation between shaft vibration displacement peak-to-peak (Spp) and runner diameter could be identified. For Kaplan units the fitted 50%-probability curve fluctuates heavily for both turbine guide bearing (TGB) and generator guide bearing (GGB). For Francis turbines the vibration values are rather constant for increasing diameter, see figure 15 and 16.

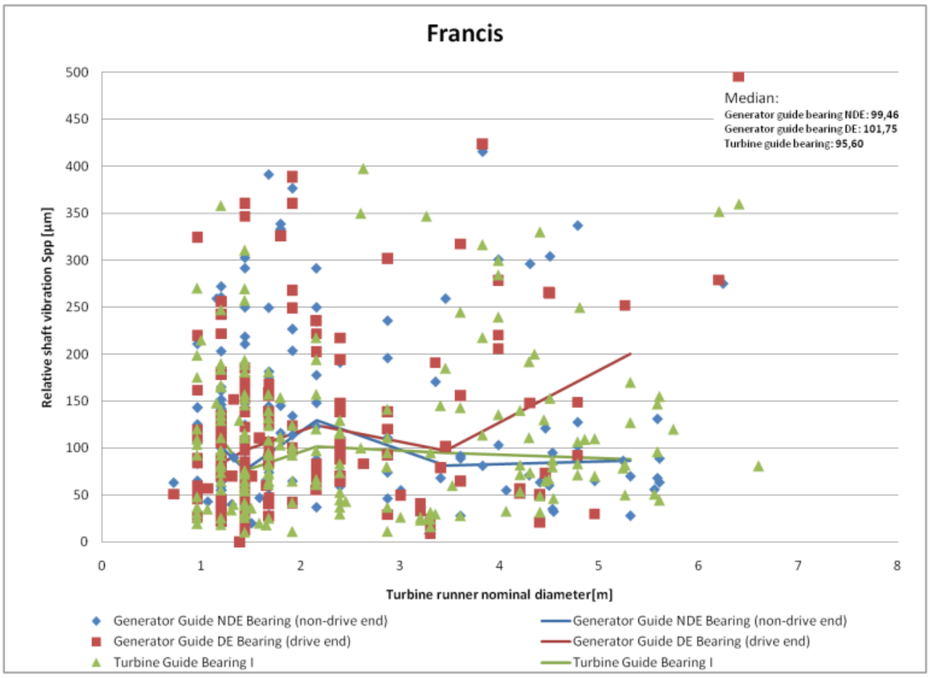


Figure 15: S_{pp} vs. Nominal diameter for Francis

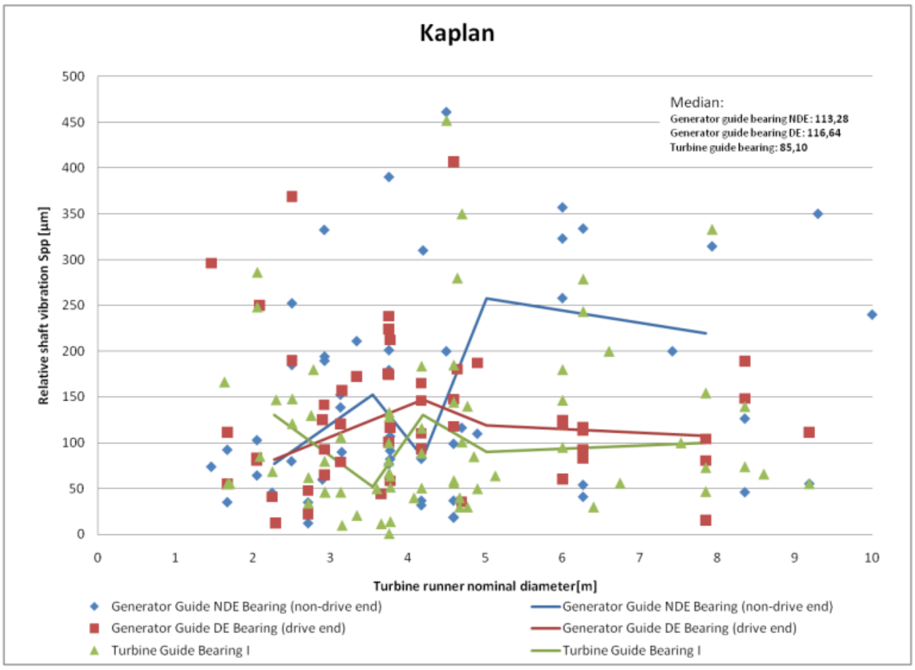


Figure 16: S_{pp} vs. Nominal diameter for Kaplan

The bearing housing vibration velocity shows decreasing values with increasing diameter for turbine guide bearing (TGB). This trend is most clear at smaller diameters up to 2m. Above this diameter the vibration trend is relatively constant. No clear trend can be recognized for generator guide bearing (GGB), see figure 17 and 18.

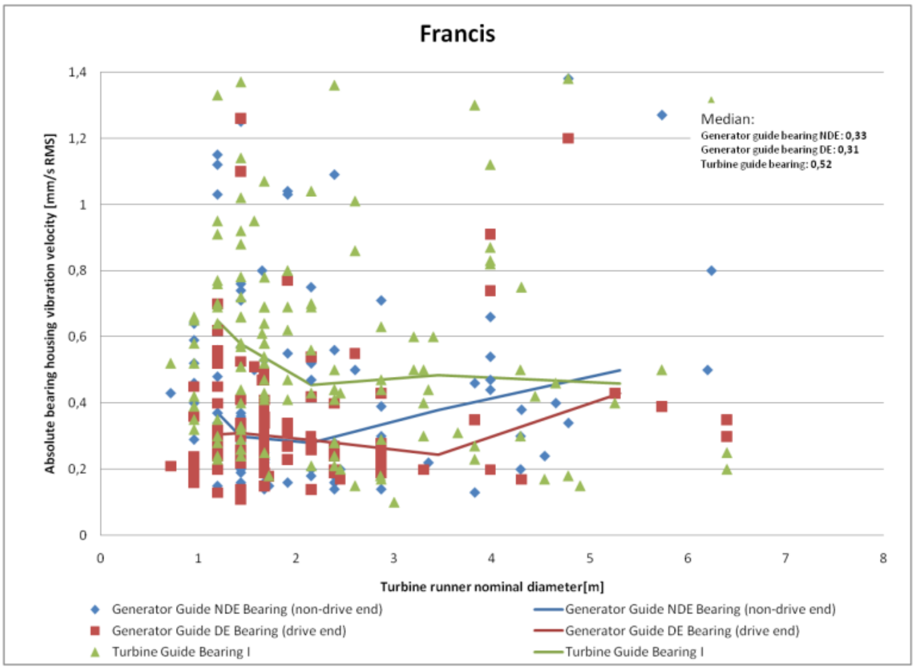


Figure 17: Vibration velocity vs. Nominal diameter for Francis

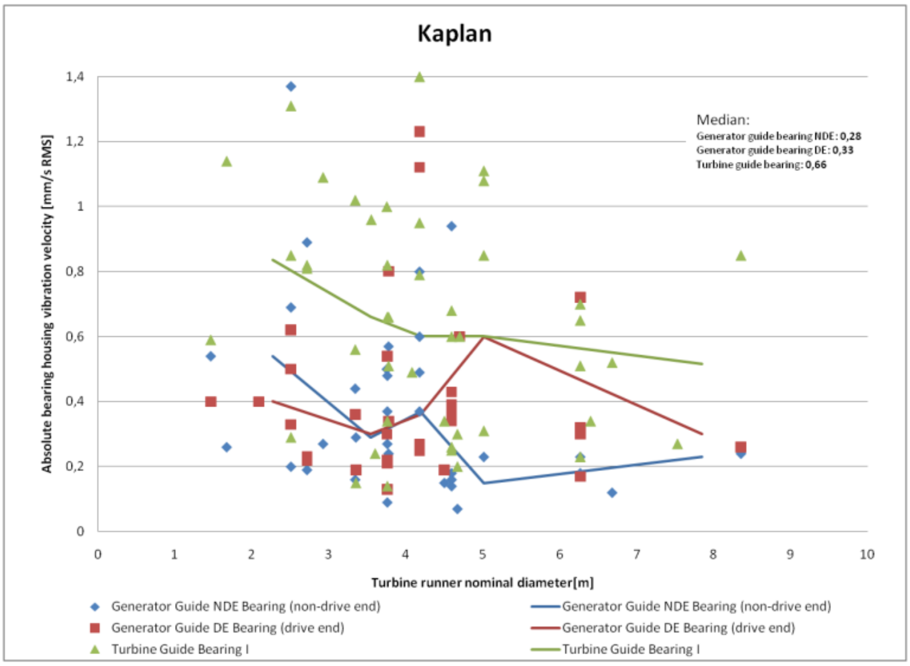


Figure 18: Vibration velocity vs. Nominal diameter for Kaplan

No clear correlation between vibration values and runner diameter could be observed.

3.1.4 Radial bearing clearance

The utilized dynamic bearing clearance (UDBC) shows a decreasing trend for all turbine types when radial bearing clearance is increasing, see figure 19 and 20.

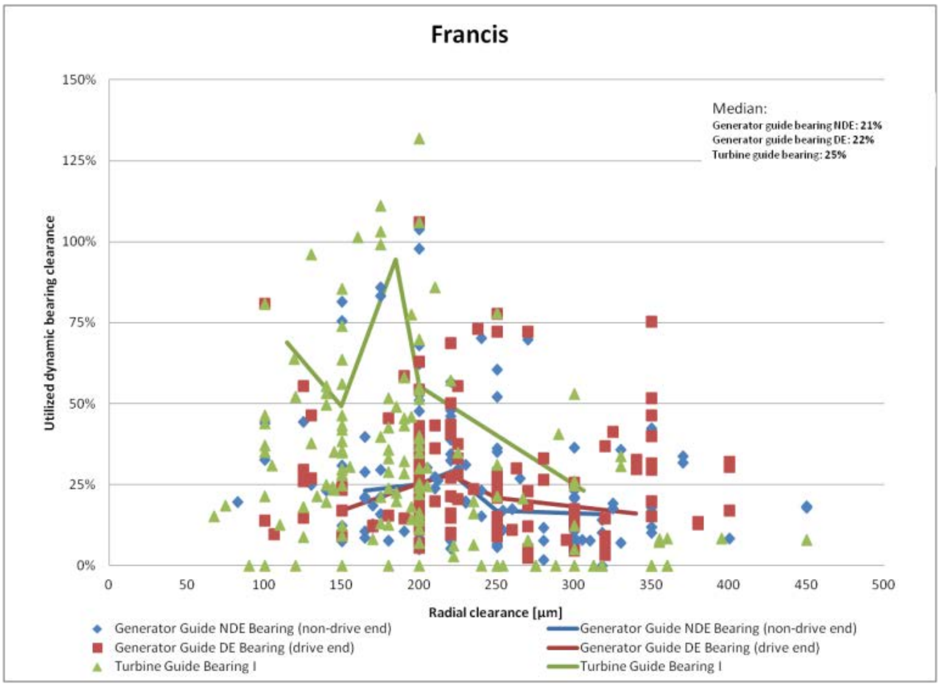


Figure 19: UDBC vs. Radial bearing clearance for Francis

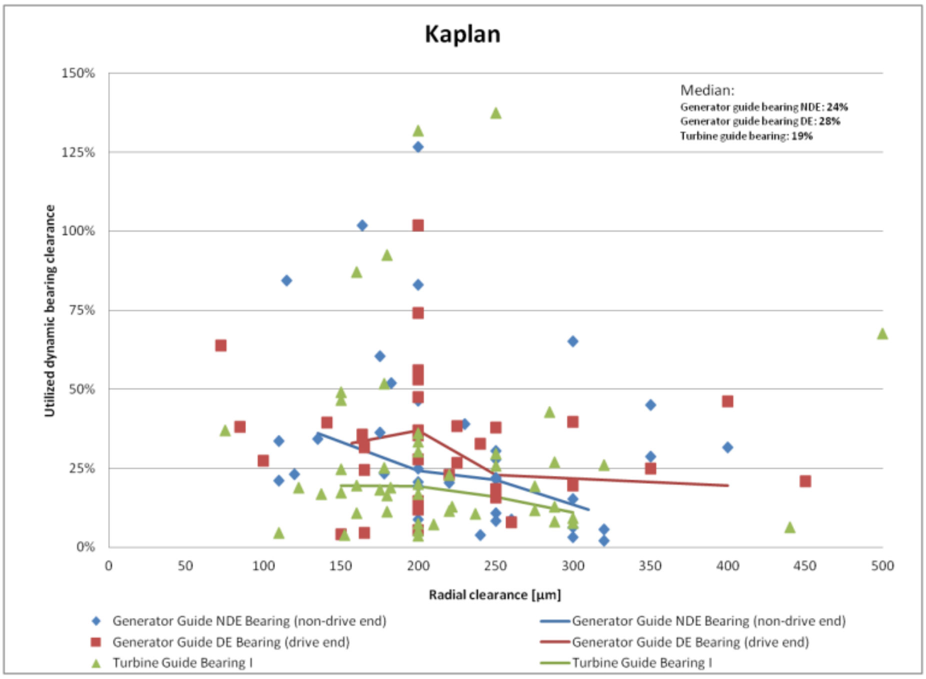


Figure 20: UDBC vs. Radial bearing clearance for Kaplan

The shaft vibration displacement peak-to-peak (S_{PP}) measurements are again very scattered and the fitted median curve fluctuates over a wide range for both Kaplan and Francis. No trend can be observed. In figure 21 and 22 the data is presented and also the limit for 100% utilized dynamic bearing clearance. Note that some measurements have larger shaft displacements than available bearing clearance, hence UDBC > 100%.

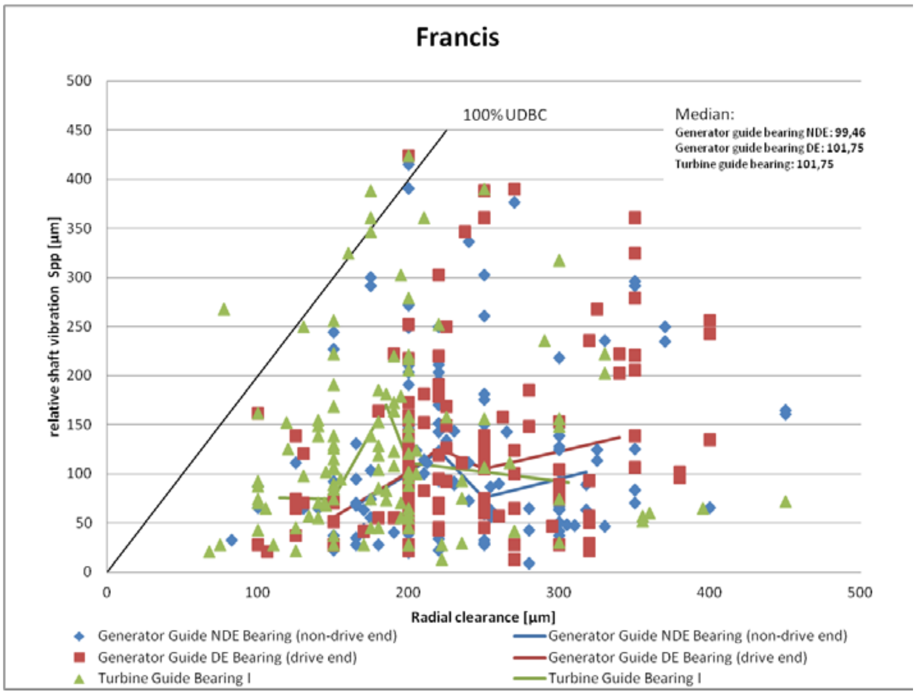


Figure 21: S_{pp} vs. Radial bearing clearance for Francis

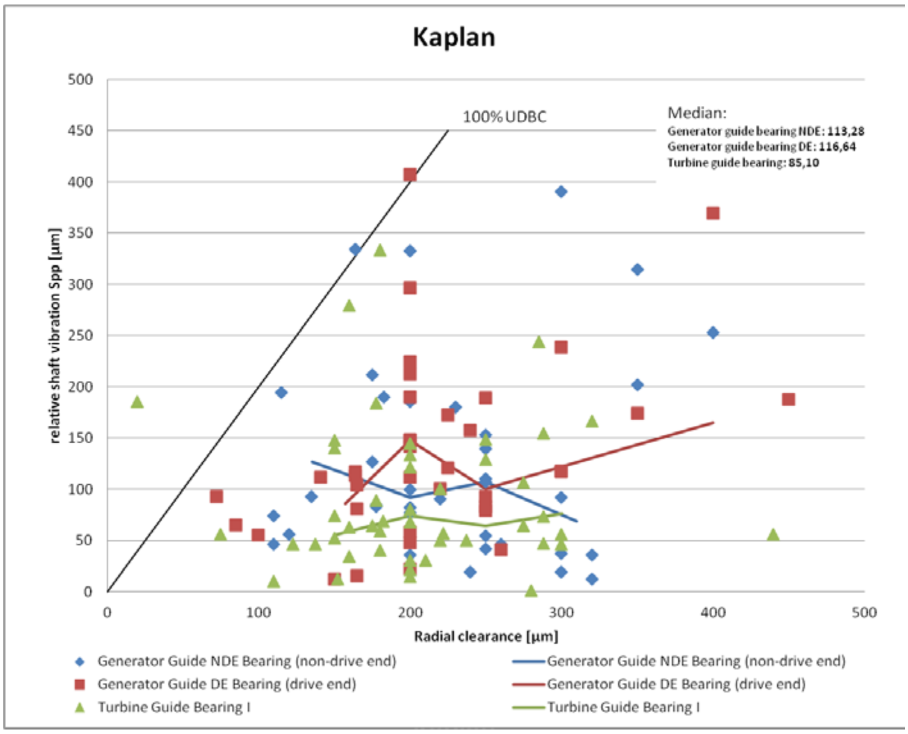


Figure 22: S_{pp} vs. Radial bearing clearance for Kaplan

The bearing housing vibration velocity shows no clear trend for increasing radial bearing clearance. For GGB the trend is increasing for Kaplan whiles for the same bearing locations for Francis the median curve is rather constant. The turbine guide bearing (TGB) in Kaplan shows a decreasing trend while the opposite is found in Francis TGB, see figure 23 and 24.

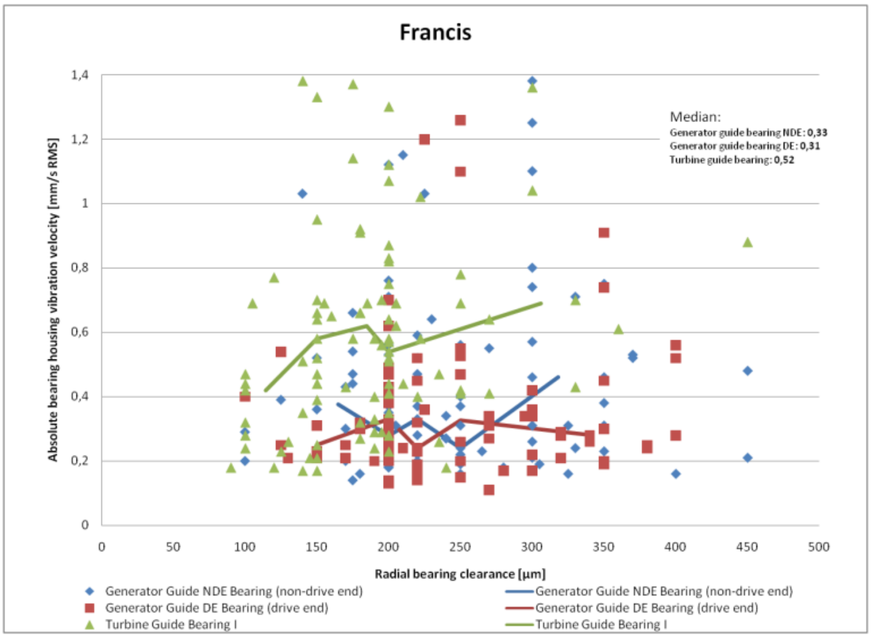


Figure 23: Vibration velocity vs. Radial bearing clearance

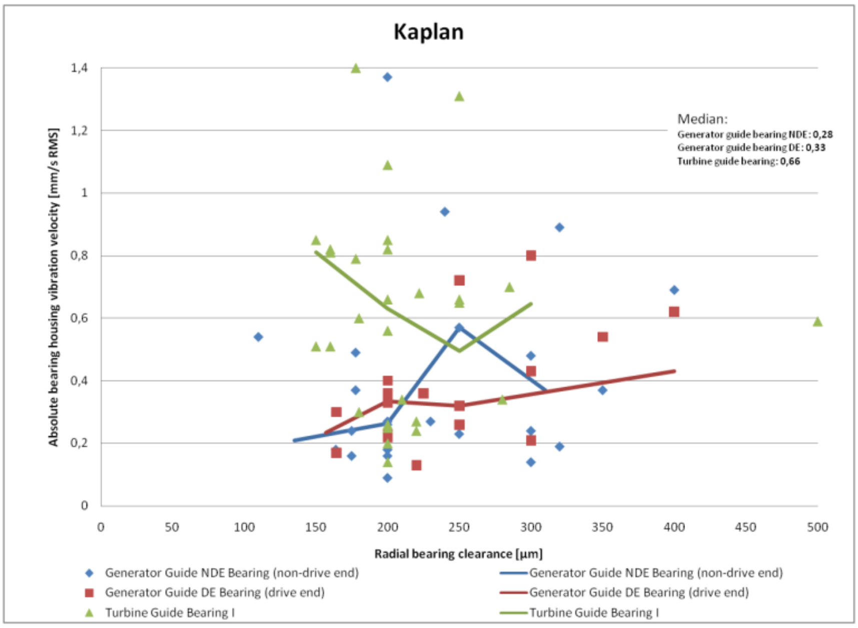


Figure 24: Vibration velocity vs. Radial bearing clearance

Most of the radial bearing clearance measurements are gathered around 200µm which makes possible trends difficult to detect.

3.1.5 General observations

- For Kaplan turbines utilized dynamic bearing clearance for the turbine guide bearing (TGB) is generally lower than for the generator guide bearings (GGB), 19% and 26% respectively. For Francis, the opposite are found, 25% and 22% respectively.
- For Kaplan shaft oscillations are lower for TGB than for GGB, 85µm and 115µm. For Francis units the vibration values are about the same, 100µm, for all bearing locations.
- The vibration velocities for Kaplan units are 0,7 mm/s for TGB and 0,3 mm/s for GGB. Corresponding values for Francis turbines are 0,5 mm/s and 0,3 mm/s, respectively.
- The turbine guide bearing shows generally higher vibration values than generator bearings. This is valid for both Francis and Kaplan units.
- Suspended type generators shows considerably lower vibration levels on both upper and lower generator bearing than semi-umbrella type units.

3.1.6 Physical approach

The analysis shows that both the shaft oscillation and the vibration velocity measurements in the database do not correlate to the studied parameters. Regarding vibration velocity it is possible to keep a physical argumentation that shows a relationship between vibration velocity and mechanical stress:

- It can be shown that the size of the supporting structure for the turbine guide bearing is proportional to the runner diameter. It can also be shown that the size of the bearing brackets for the generator guide bearings is proportional to the rotor diameter. If all bearing brackets have similar design criteria and material properties, Hooke's law implies that the permissible strain will be constant. However, since strain and displacement is related through size, increasing size will result in larger displacements. Consequently, the allowed displacement is proportional to the turbine or generator diameter.
- Previous studies have shown that circumferential velocity for the turbine is rather constant for all types of reaction turbines. This implies that the rotational speed is inversely proportional to the diameter of the runner.
- The combined conclusion for this argumentation is that large machines experience high deflections with low rotational frequency whereas small machines experience small deflections with high rotational frequency. The stress levels in the supporting structure is however equal for all machine sizes and thus the vibration velocity is constant.

Regarding shaft oscillation and the lack of correlation with bearing journal diameter, the physical explanation is that all bearing clearances are designed for supplying a carrying oil film even at small shaft eccentricities [1]. In conjunction to this the IEEE Std 810-1987 (R2001) [2] specifies the total allowable run out for a shaft system to 76 µm. This is a maximum value independent of the shaft diameter. Clearly, the total allowable run out must be accommodated within a normal bearing clearance.

3.1.7 Statistical approach

Since no clear correlation between parameters and measured vibration data were observed the aim was to find a probability function that could fit the measured data set. A good probability distribution could repair a database with too few data. Each measured vibration value is assumed to be a stochastic variable and hence form a continuous distributed sample. The sample is then discretized by assigning frequency values to intervals of equal distance as to form a histogram. It is clear that all samples have a positive skewness which indicates that the tail on the right side is longer than the left side and the majority of the values lie to the left of the mean. The curve fitting process was done by software routines and the best fit was produced by the Burr distribution, see figure 25 and 26.

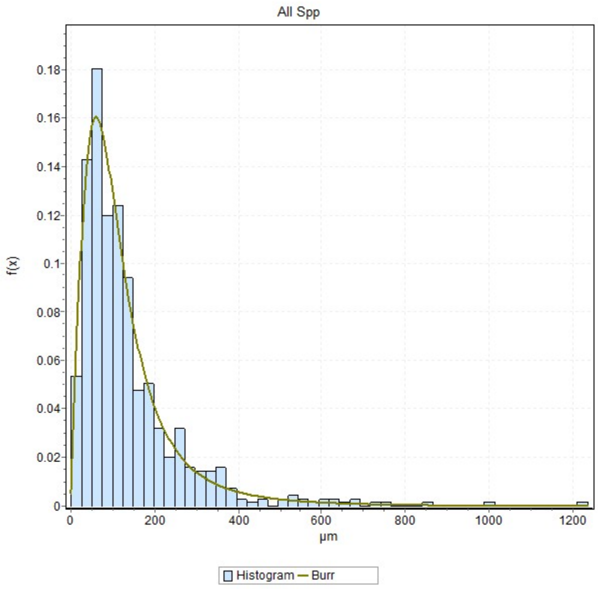


Figure 25: Discretized sample of shaft oscillation and projected the fitted Burr-distribution

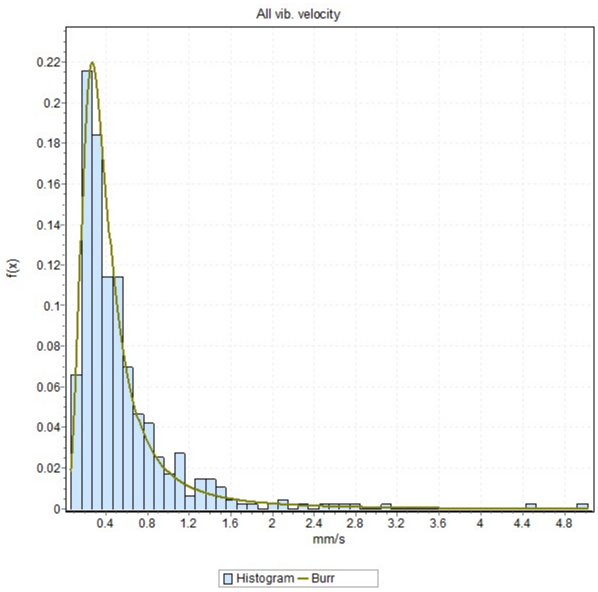


Figure 26: Discretized sample of vibration velocity and projected the fitted Burr-distribution

The Burr distribution is applied in a variety of areas such as reliability studies and failure time modeling. Unlike other failure time distributions such as Weibull and Rayleigh, the Burr distribution contains two shape parameters. This makes the distribution more versatile when fitted onto a sample. Below, in figure 27, is the fitted Burr distribution for vibration velocities with definitions on the mode, mean and median values.

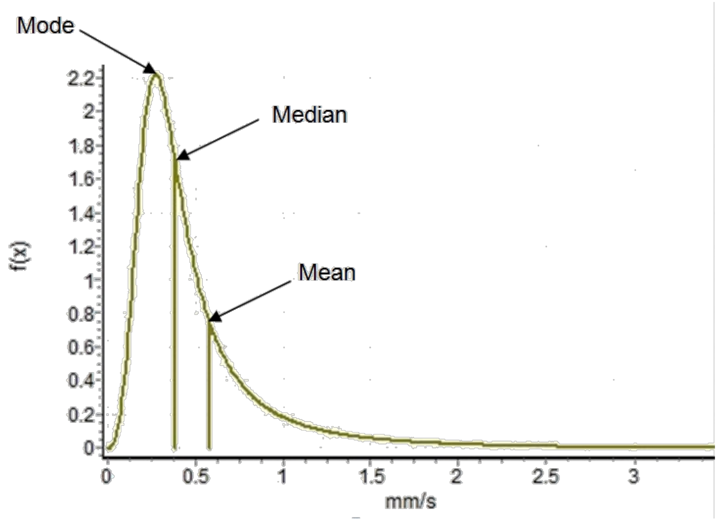


Figure 27: Definitions of mode, mean and median

In table 4, the values mean, median and mode is summarized for each data set. The median value can be derived from the measurement data or from the distribution. It is separating the greater and lesser halves in the data set. The mean is also calculated from the measured data set. The mode and the median values are taken from the probability density function i.e. the Burr distribution. Since the distribution have a positive skew, the mode (peak of the distribution) will lie to the left of the median value.

Each data set and distribution is presented in appendix 2.

Shaft vibration Spp [µm]					
Data set	Type	Measured values		From distribution func.	
		Mean	Median	Mode	Median
Generator guide bearing	Francis	138	100	62	100
	Kaplan	163	117	71	122
Turbine guide bearing	Francis	115	93	62	91
	Kaplan	139	85	45	93
Vibration velocity [mm/s]					
Data set	Type	Measured values		From distribution func.	
		Mean	Median	Mode	Median
Generator guide bearing	Francis	0,46	0,31	0,23	0,31
	Kaplan	0,46	0,32	0,22	0,32
Turbine guide bearing	Francis	0,67	0,52	0,40	0,53
	Kaplan	0,70	0,66	0,49	0,62

Table 4: Mean-, median- and mode- values for each data set and bearing location

An approach in controlling the accuracy for the distribution is made in table 5. The method used is to compare the measured values (median and mean) with the corresponding calculated values from the probability density function (median and mean).

Shaft vibration Spp, accuracy of distribution			
Data set	Type	Median	Mean
Generator guide bearing	Francis	1,00	0,98
	Kaplan	0,96	0,98
Turbine guide bearing	Francis	1,01	1,00
	Kaplan	0,92	0,97
Vibration velocity, accuracy of distribution			
Data set	Type	Median	Mean
Generator guide bearing	Francis	1,03	0,90
	Kaplan	1,00	0,90
Turbine guide bearing	Francis	0,98	0,99
	Kaplan	1,06	1,00

Table 5: Accuracy of distribution. Calculated as median (measured) / median (from distribution) and mean (measured) / mean (from distribution)

The accuracy for the Burr distribution is by this method in the range of 100-90%. The best fit is produced for Francis turbines when shaft vibration is considered.

For safe and reliable running of the machine under normal operation conditions requires that the vibration values should remain below certain limits. According to ISO 7919-5 and ISO 10816-5, the limits are defined by zone boundary values. The ratios between the zone boundaries were, according to the standards, found through discussions within the workgroup and with experts in the field. The ratios are 1.6x and

2.5x a specific reference value. 2.5 times the reference value corresponds to increase of turbine vibration level that leads to essential change of its vibration state. Also, the ratio of the product of the two suggested values to 2.5 is equal to the ratio of 2.5 to 1.6, hence the ratio is within the Golden ratio which has a huge number of applications in the nature. The reference value may be a subject of discussion, in this report the suggestion is to use either the median value or the mode value. Table 6 below presents the percentiles and the actual values for 1.6x and 2.5x the reference value.

Shaft oscillation Spp [µm]					
		1.6x		2.5x	
Data set	Type	Mode	Median	Mode	Median
Generator guide bearing	Francis	50% (99)	73% (160)	72% (155)	88% (250)
	Kaplan	47% (114)	73% (195)	69% (178)	88% (304)
Turbine guide bearing	Francis	55% (99)	75% (146)	71% (155)	91% (228)
	Kaplan	39% (72)	71% (148)	59% (113)	85% (231)
Vibration velocity [mm/s]					
		1.6x		2.5x	
Data set	Type	Mode	Median	Mode	Median
Generator guide bearing	Francis	61% (0,37)	76% (0,50)	82% (0,58)	89% (0,78)
	Kaplan	56% (0,35)	75% (0,51)	78% (0,55)	88% (0,80)
Turbine guide bearing	Francis	63% (0,64)	78% (0,85)	85% (1,00)	92% (1,33)
	Kaplan	66% (0,78)	80% (0,99)	89% (1,23)	96% (1,55)

Table 6: Percentiles and actual values for 1.6x and 2.5x the reference values

Using the mode as reference value leads to considerably low boundary values, sometimes lower than the median. Using the median value produces more realistic values for reference. 1.6 corresponds to around 75% probability and 2.5 corresponds to around 90% probability.

Figure 28 and 29 shows the boundaries for 1.6x and 2.5x reference value, here the 50%-probability value, for both shaft vibration and vibration velocity, is used.

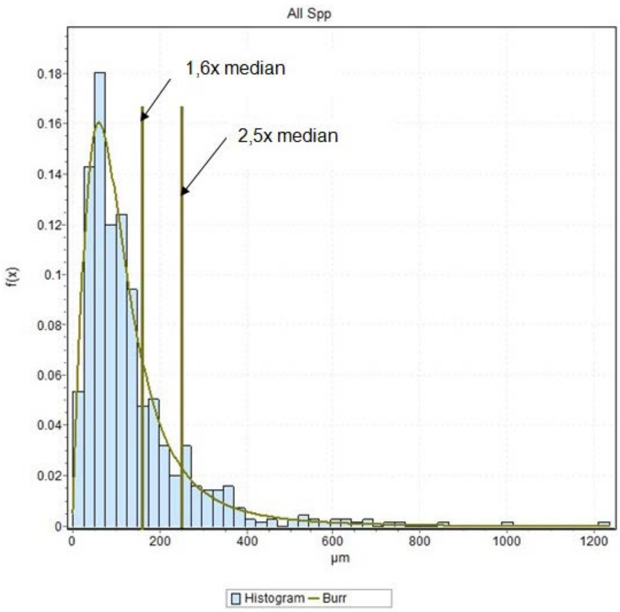


Figure 28: Boundary for 1.6 and 2.5 times the reference value (160 resp. 250µm)

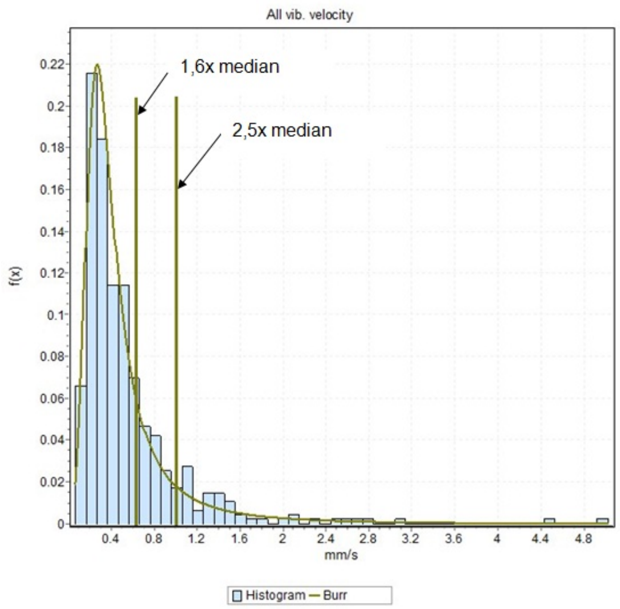


Figure 29: Boundary for 1.6 and 2.5 times the reference value (0.6 resp. 1.0mm/s)

3.2 ANALYZE AN UNFILTERED AND MORE RECENT VERSION OF THE DATABASE

3.2.1 Medium vibration levels for turbine types and shaft orientation

For step 3 (Analyse an unfiltered and more resent version of the database) of the work scope in this project database revision F was analyzed. For the analysis the median value was calculated for the groups defined in table 3. Figure 30-33 shows the vibration levels for the specific turbine types and shaft orientations. Note that units marked as "problem" is not included in the dataset.

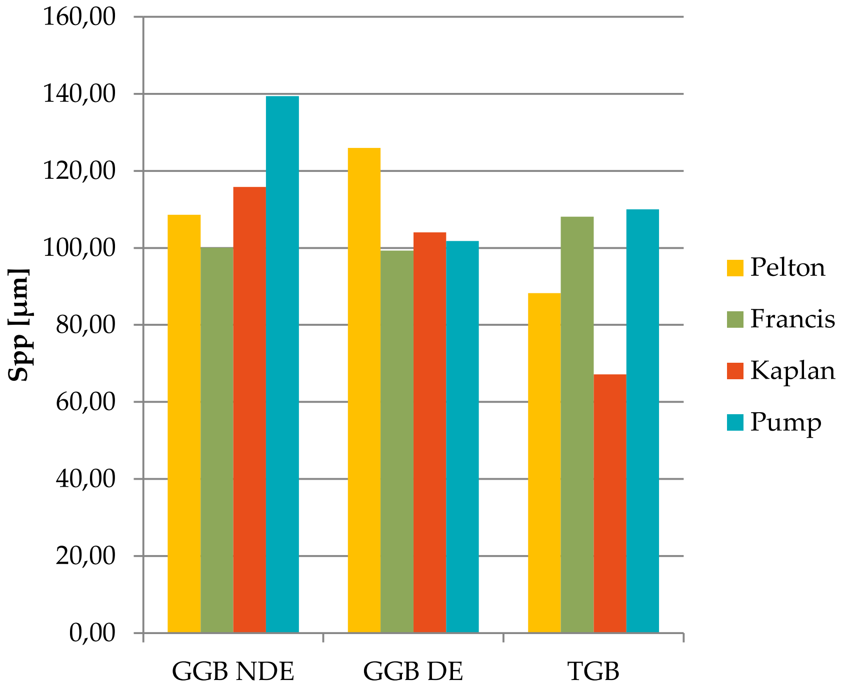


Figure 30: Level of Spp for vertical units

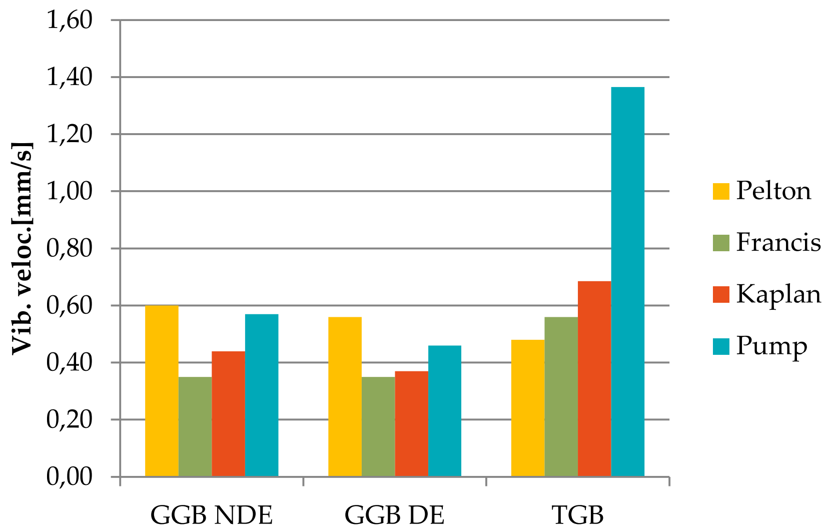


Figure 31: Vibration velocity level for vertical units

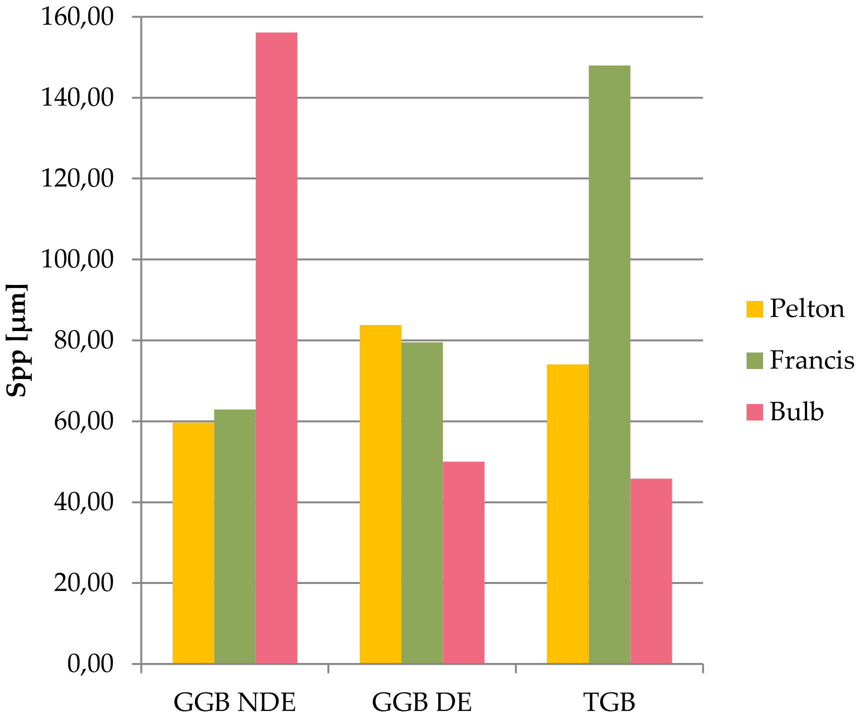


Figure 32: Level of S_{pp} for horizontal units

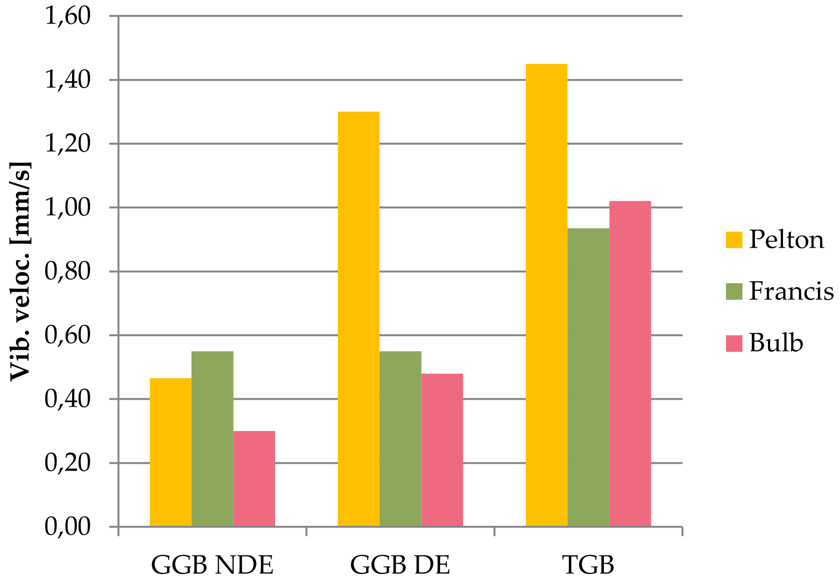


Figure 33: Vibration velocity level for horizontal units

The median values are summarized in table 7 below.

Vertical units						
	GGB NDE		GGB DE		TGB	
	Spp	Vrms	Spp	Vrms	Spp	Vrms
Pelton	109	0,60	126	0,56	88	0,48
Francis	100	0,35	99	0,35	108	0,56
Kaplan	116	0,44	104	0,37	67	0,69

Pump	139	0,57	102	0,46	110	1,37
Horizontal units						
	GGB NDE		GGB DE		TGB	
	Spp	Vrms	Spp	Vrms	Spp	Vrms
Pelton	60	0,47	84	1,30	74	1,45
Francis	63	0,55	80	0,55	148	0,94
Bulb	156	0,30	50	0,48	46	1,02

Table 7: Median values for the relevant groups

3.2.2 Comparison of median values between database revision E and F

The filtered dataset from database revision E which only contains measurements of units in the best operating range is compared with the complete database revision F, see figure 34-35. The result should be used to validate the median method.

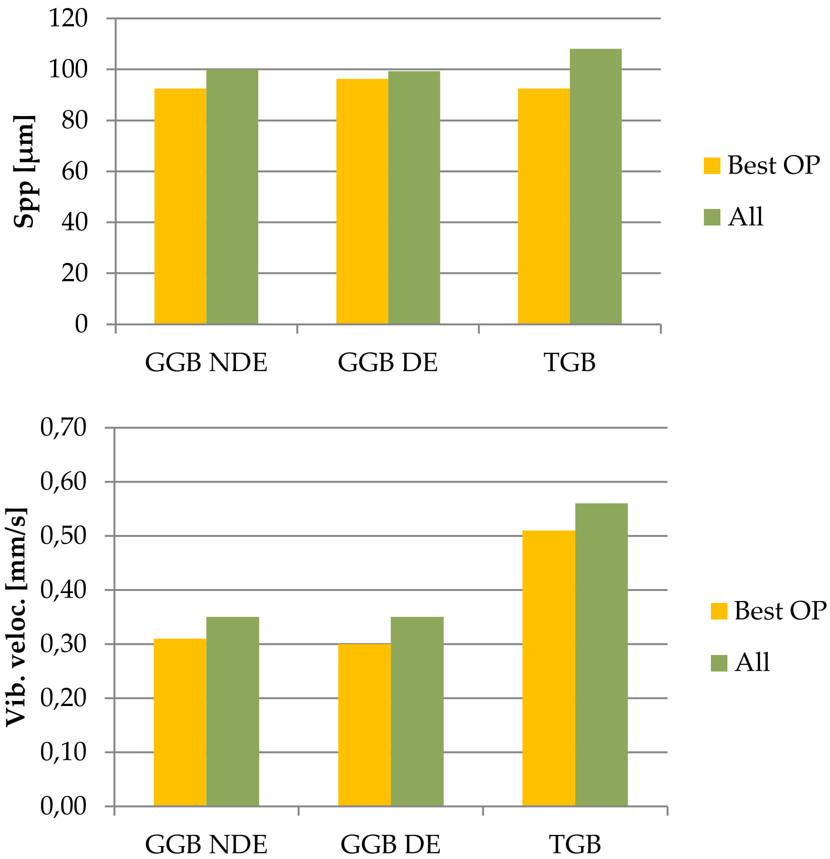


Figure 34: Comparison of median values for vertical Francis units for dataset only containing measurements at best operation point and dataset containing all measured values

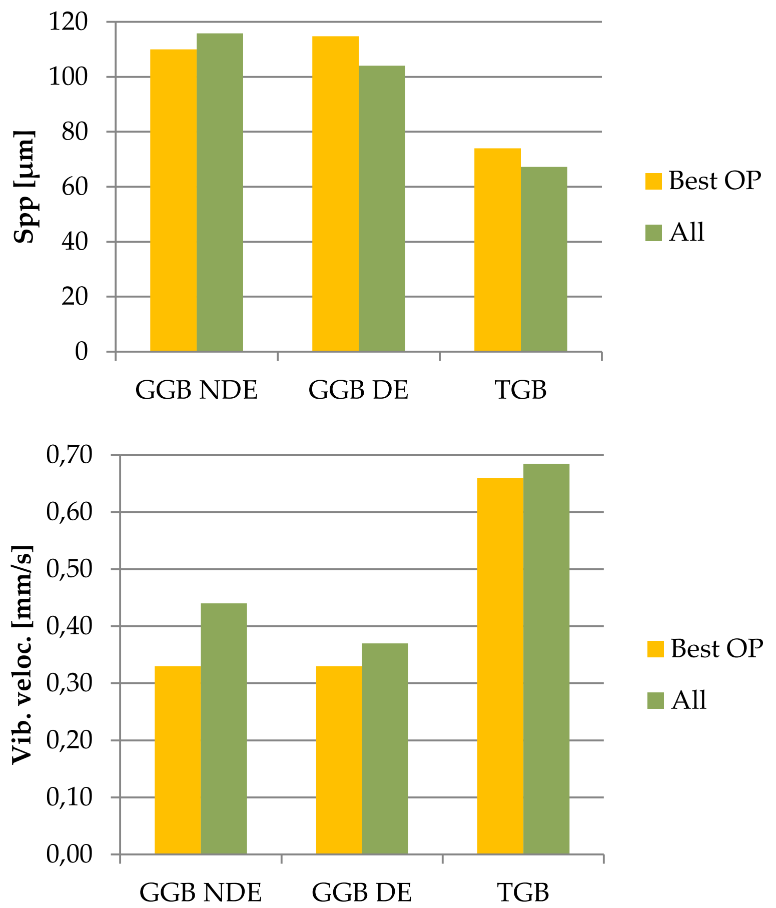


Figure 35: Comparison of median values for vertical Kaplan units for dataset only containing measurements at best operation point and dataset containing all measured values

3.2.3 Distribution of measured values and units marked as "problem"

Figure 36 and 37 below shows the distribution of measurements on generator guide bearings (GGB) and turbine guide bearings (TGB) for vertical Francis and Kaplan units. Both normal and units marked as problem is included in the distribution. Projected is the proportion of problem units expressed as percentage of the total number of measurements. Projected is also the median value and the proposed boundary limits.

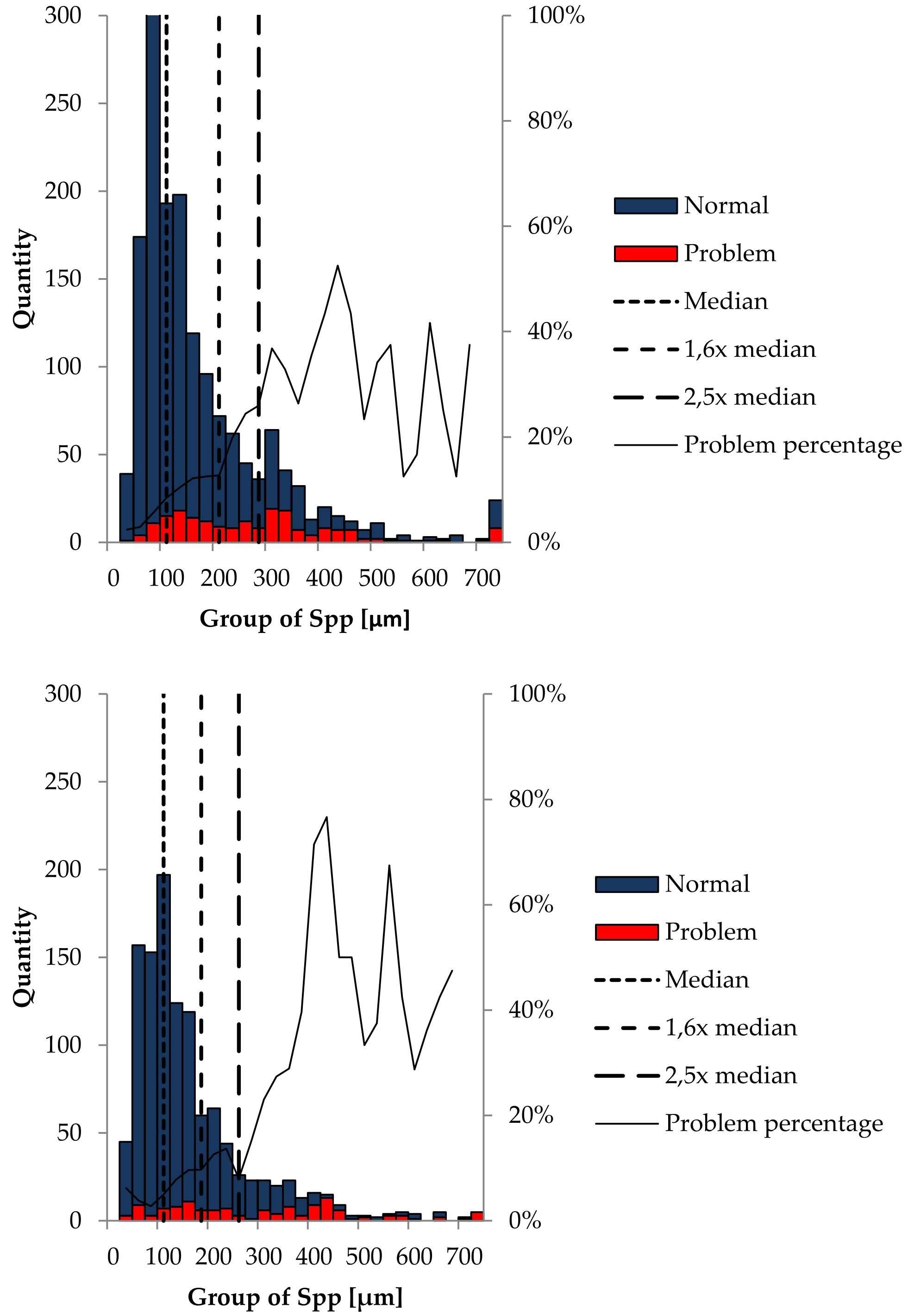
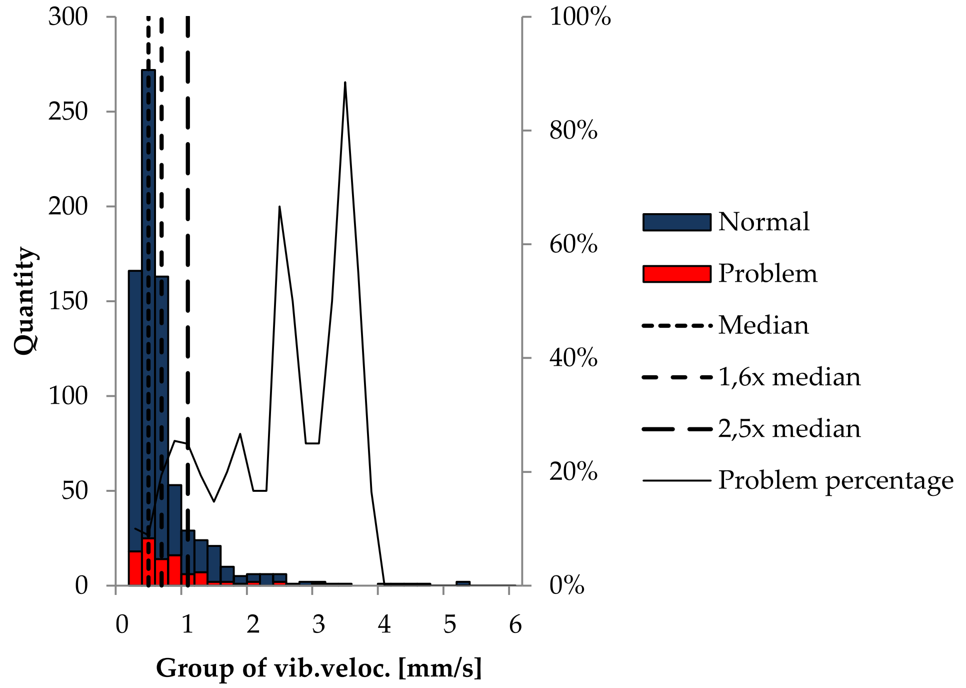


Figure 36: Distribution of measurements for "normal" units (blue) and units marked as "problem" (red). The solid black curve is a representation of the proportion of problem units in the distribution. Distribution at top is for generator bearings and bottom is for turbine guide bearings.



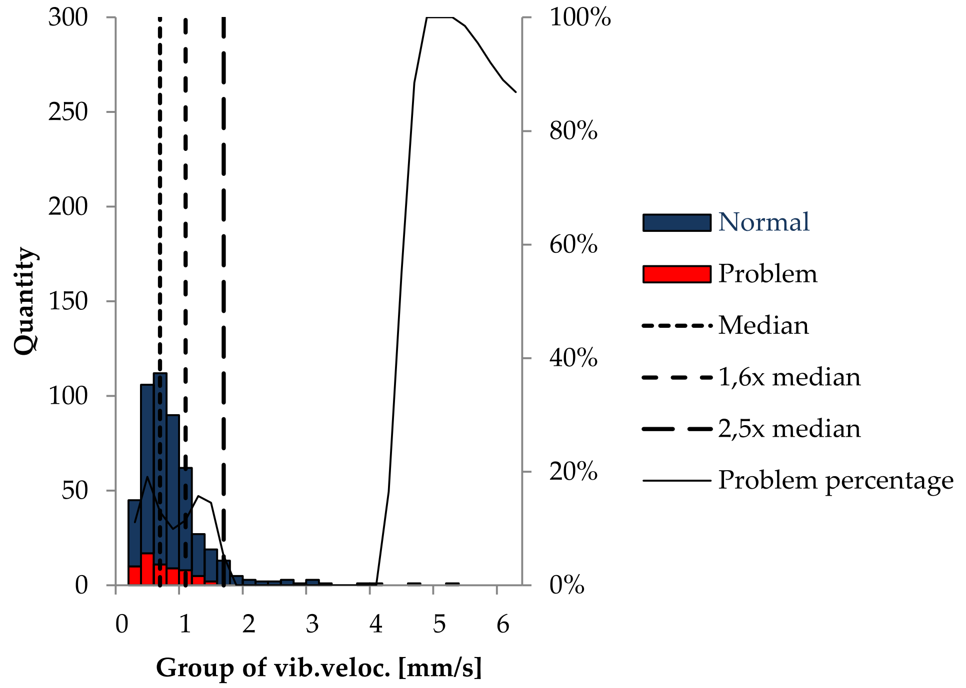


Figure 37: Distribution of measurements for "normal" units (blue) and units marked as "problem" (red). The solid black curve is a representation of the proportion of problem units in the distribution. Distribution at top is for generator bearings and bottom is for turbine guide bearings.

3.3 ANALYZE THE MOST RECENT DATABASE WITH METHODS ESTABLISHED IN EARLIER STEPS IN ORDER TO PROPOSE ACTION LIMITS FOR THE DIFFERENT MACHINE TYPES

3.3.1 Median values from the database revision J

The median values are calculated from the complete filtered revision J of the database, see chapter 2.3.3. Table 8 and 9 shows the vibration levels and action limits for 1.6x and 2.5x the median value for the specific turbine types and shaft orientations. Note that units marked as "problem" is not included in the dataset. Median values based on less than 10 measurements are highlighted in red and values based on 10-30 measurements are highlighted in yellow.

Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Francis vertical	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	926	537	759	328	258	287
Median	108	111	99	0,6	0,3	0,3
Median x 1.6 (A/B)	174	178	158	0,9	0,5	0,5
Median x 2.5 (C/D)	271	278	247	1,4	0,8	0,9
Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Pump-Turbine vertical	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	228	173	185	155	102	145
Median	104	97	136	1,2	0,4	0,6
Median x 1.6 (A/B)	166	155	218	1,9	0,7	0,9
Median x 2.5 (C/D)	259	243	341	3,0	1,1	1,5
Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Kaplan vertical	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	253	161	113	129	82	102
Median	68	105	102	0,7	0,4	0,4
Median x 1.6 (A/B)	109	168	163	1,1	0,6	0,7
Median x 2.5 (C/D)	170	263	255	1,8	1,0	1,1
Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Pelton vertical	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	29	31	32	35	37	44
Median	83	88	107	0,5	0,5	0,6
Median x 1.6 (A/B)	133	141	171	0,8	0,8	1,0
Median x 2.5 (C/D)	208	221	267	1,2	1,3	1,5
Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Pump vertical	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	30	18	36	2	14	6
Median	121	106	111	0,1	0,4	0,4
Median x 1.6 (A/B)	194	170	178	0,2	0,6	0,6
Median x 2.5 (C/D)	303	266	278	0,3	0,9	1,0

Table 8: Median values and action limits for 1.6x and 2.5x the median value for vertical units

Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Francis horizontal	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	69	112	139	37	35	27
Median	173	80	65	0,9	0,5	0,6
Median x 1.6 (A/B)	277	127	104	1,4	0,8	1,0
Median x 2.5 (C/D)	432	199	162	2,3	1,3	1,5
Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Bulb horizontal (*)	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	42	29	24	34	24	33
Median	52	140	133	1,6	0,4	0,3
Median x 1.6 (A/B)	83	224	213	2,6	0,6	0,5
Median x 2.5 (C/D)	130	350	333	4,1	1,0	0,8
(*) Double regulated						
Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Pelton horizontal	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	34	39	36	39	47	47
Median	74	83	61	1,0	1,3	0,7
Median x 1.6 (A/B)	118	133	97	1,6	2,1	1,1
Median x 2.5 (C/D)	185	208	151	2,4	3,3	1,8
Machine type:	Shaft oscillation S_pp (µm)			Bearing vibration V_rms (mm/s)		
Pump horizontal	T1	GE - DE	GE - NDE	T1	GE - DE	GE - NDE
Number of measurements	26	30	39	-	4	4
Median	194	73	59	-	0,3	0,2
Median x 1.6 (A/B)	311	117	95	-	0,5	0,4
Median x 2.5 (C/D)	486	183	148	-	0,7	0,6

Table 9: Median values and action limits for 1.6x and 2.5x the median value for horizontal units

The calculated median values for the different types of machines and bearing locations are generally at the same level as calculated from previous revisions. Exceptions are shaft oscillations for Bulb units which have increased values versus previous revisions. Note that although the vast number of measurements in database revision J, there are still machine types that lack measurements for determination of action limits. Although the database has been substantially increased the number of measurements of bearing housings is the same as for previous revision.

3.3.2 Analysis for determination of median values per machine group

During discussions with the international work group, JWG1, there were requests for presenting separate action values for housing vibrations for the different machine groups. During this analysis an examination whether there existed a common factor for the relationship between the groups was done. Since many of the measurements in the database lacks information of machine groups, several filtrations was performed, see table 10.

Filtration:	7 R	8a R			8b R		9 R
	Information on machine vibration problems known at measurement	IEC Machine type classification			ISO Machine Group		Shaft orientation
1	Empty	K	F	F + K	3	4	V
2	Empty	K	F	F + K	3	4	V + empty
3	Empty	K	F	F + K	3 + empty	4 + empty	V
4	Empty	K	F	F + K	3 + empty	4 + empty	V + empty

Table 10: Explination of the different types of filtrations

None of the chosen filtrations could present a dataset from which there could be a clear change in vibration magnitude between the groups, see table 11-13. Note that cells in red are based on ≤ 10 actual measurements and cells in yellow are based on 11-30 actual measurements.

						GGB NDE				Factor (group 4 /group 3)
Filtration:	7 R	8a R	8b R	9 R	number	Vib.velocity RMS median	number			
1	empty	K	3	V	76	0,45	14			0,00
2	empty	K	3	V + empty	76	0,45	14			0,00
3	empty	K	3 + empty	V	673	0,44	100			0,78
4	empty	K	3 + empty	V + empty	703	0,45	102			1,00
						GGB NDE pos.1		GGB DE pos.2		Factor (pos.1 / pos.2)
Filtration:	7 R	8a R	8b R	9 R	number	Vib.velocity RMS median	number	Vib.velocity RMS median	number	
1	empty	K	4	V	83	0	0	0	0	-
2	empty	K	4	V + empty	83	0	0	0	0	-
3	empty	K	4 + empty	V	680	0,34	86	0,34	69	1,00
4	empty	K	4 + empty	V + empty	710	0,45	88	0,37	73	1,20

Table 11: Type of filtration, calculated median value and common factor between the groups and for bearing positions.

						GGB NDE			Factor (group 4 /group 3)
Filtration:	7 R	8a R	8b R	9 R	number	Vib.velocity RMS median	number		
1	empty	F	3	V	381	0,45	14		1,78
2	empty	F	3	V + empty	381	0,45	14		1,78
3	empty	F	3 + empty	V	3493	0,33	279		1,00
4	empty	F	3 + empty	V + empty	3666	0,33	280		1,00

						GGB NDE pos.1		GGB DE pos.2		Factor (pos.1 / pos.2)
Filtration:	7 R	8a R	8b R	9 R	number	Vib.velocity RMS median	number	Vib.velocity RMS median	number	
1	empty	F	4	V	91	0,80	3	0,54	18	1,48
2	empty	F	4	V + empty	91	0,80	3	0,54	18	1,48
3	empty	F	4 + empty	V	3203	0,33	268	0,33	251	1,00
4	empty	F	4 + empty	V + empty	3376	0,33	269	0,33	251	1,00

Table 12: Type of filtration, calculated median value and common factor between the groups and for bearing positions.

						GGB NDE			Factor (group 4 /group 3)
Filtration:	7 R	8a R	8b R	9 R	number	Vib.velocity RMS median	number		
1	empty	F + K	3	V	457	0,45	28		1,80
2	empty	F + K	3	V + empty	457	0,45	28		1,80
3	empty	F + K	3 + empty	V	4166	0,37	379		0,99
4	empty	F + K	3 + empty	V + empty	4369	0,37	382		1,00

						GGB NDE pos.1		GGB DE pos.2		Factor (pos.1 / pos.2)
Filtrering:	7 R	8a R	8b R	9 R	number	Vib.velocity RMS median	number	Vib.velocity RMS median	number	
1	empty	F + K	4	V	174	0,80	3	0,65	8	1,23
2	empty	F + K	4	V + empty	174	0,80	3	0,65	8	1,23
3	empty	F + K	4 + tomma	V	3883	0,37	354	0,33	310	1,11
4	empty	F + K	4 + tomma	V + empty	4086	0,37	357	0,33	314	1,12

Table 13: Type of filtration, calculated median value and common factor between the groups and for bearing positions.

Since no clear change in vibration magnitude between the groups could be detected the proposed action limits in table 8 and 9 should be valid for all machine groups.

4 Conclusions

No clear correlation between vibration values and the unit specific parameters such as head, rotational speed, runner diameter and radial bearing clearance could be observed. The lack of correlation implies paradoxically that both shaft oscillations and vibration velocities are relevant parameters:

- It is common to use functions that cover the trends and coefficients for the calibration. An indication that the function is appropriate is that the coefficients are independent of all parameters. This can be applied for the physical parameters vibration level and shaft oscillations.

In section 3.1.6, a physical argumentation is presented based on stress levels in the supporting structure for the guide bearings and that the circumferential velocity for the turbine is rather constant for all types of reaction turbines. The conclusion from this explanation is summarized in figure 38 below.

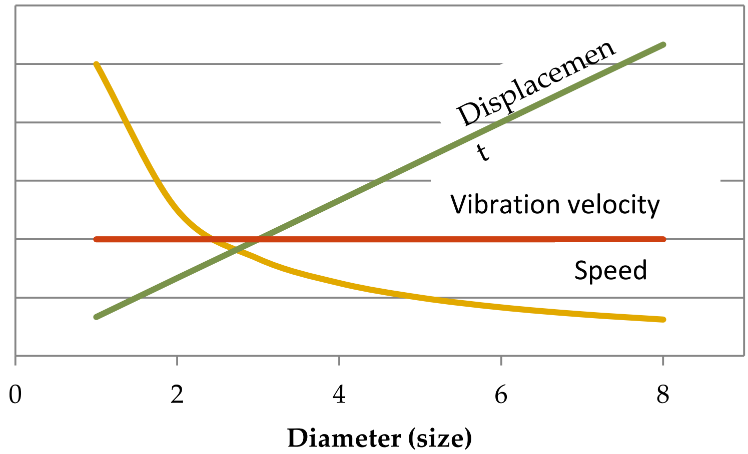


Figure 38: The relation between size, displacement and speed

The argumentation is further described in the presentation ”JWG1 – Vibrations on hydraulic Machines, The physical relevance for the vibration velocity parameter”.

Several shortcomings can be identified for the parameter utilized dynamic bearing clearance. High magnetic unbalance in the generator and high hydraulic unbalance in the turbine gives small shaft oscillations and small UDBC, bearing load can however be very high. A poorly aligned shaft arrangement can also give low values on shaft oscillations and UDBC, although high bearing load.

Also a physical explanation of the shaft oscillations not correlating to the bearing journal diameter is presented in section 4.6. The conclusion from this is that all bearing clearances are chosen so that even small eccentricities will give rise to a supporting oil film. The clearance is thus not a function of size. The minimum clearance is limited by the different expansion rates of shaft and bearing due to the temperature rise at start of the unit. It should also be mentioned that the majority of radial clearance values in the database is specified as “design value”. The actual bearing clearance at the specific measurement is therefore not known. This might explain some of the situations when the shaft oscillations are larger than the specified bearing clearance, UDBC > 100%.

The future standard has to distinguish at least between turbine type (Francis, Kaplan, Bulb, Pelton and Pump) and between bearing location (turbine bearing and generator bearings). Preferable is also a separation into shaft orientation (horizontal and vertical).

A statistical study of database revision E found the measured data to be Burr-distributed. Vibration reference values are here suggested to be based on the median value for at least turbine and generator bearings. Actions should be undertaken if the actual vibration value exceeds 1.6 and 2.5 times the reference value:

- 1.6 times the reference value corresponds roughly to the 75 percentile
- 2.5 correspond approximately to the 90 percentiles.

The suggested boundaries are here significantly lower than the current boundary zones in the existing standard. A more in depth and adequate statistical analysis could be made in order for establishing valid vibration reference values. However, the analysis shows that the median value for the shown Burr-distributions is very close to the mean values for the datasets. And as the median value method objectively excludes extreme values this method is promoted for finding the adequate reference values. The method is also verified by figure 34 and 35 where the median value for a dataset with only measurements in best operating range is compared with an unfiltered dataset. The resulting median value is nearly equal for the two compared datasets.

An analysis of the distribution of units marked as "problem" in the database revision F was also conducted. It was shown that problem units were evenly distributed over the complete range of measured values. Surprisingly, machines labeled as ”problem” in the database do not have exceptionally high vibration levels if compared to other measured values which are considered to be ”normal”. However, the proportion of machines marked as "problem" increases with higher vibration values. At approximately 2.5 times the median value the proportion of problem units increases more radically. This could prove that the proposed boundary levels 2.5 and 1.6 times the median value makes sense.

During 2013-2014, analysis of database revision J was conducted. Since the number of measurements was increased with this version the aim of the analysis was to find reference values which could be used for producing action limits. These limits were produced by using the boundary levels recommended from earlier analysis and the median values calculated from the increased database revision J. The recommended action limits from this analysis is generally at the same level as calculated from previous revisions. Exceptions are shaft oscillations for Bulb units which have increased values versus previous revisions. Although the database has been substantially increased the number of measurements of bearing housings is the same as for previous revision.

5 Future work

- During analyze work the database has been revised a number of times. Current database was released 2013-11-20 and contains 7355 measurements. If the database is revised with even more measurements, the median method could be applied on the latest revision for verification of action limits.
- The data suppliers should refine their definition for machines marked as "problem" in the database.
- Identification of relevant bearing groups (turbine/generator, suspended/umbrella, closed shell/tilting pad). It is possible from the database to filter out these groups which then can be internally analysed for parameter correlation.
- Identification of the relationship between the vibrations of the generator guide bearings and the turbine guide bearing. This should then render a physical explanation of the relationship. The rotordynamic behaviour of a shaft system could be taken into consideration during this analysis.
- Explanation of measured shaft movements that is larger than the specified available bearing clearance
- An identification of the impact of the current requirements of IEC/ISO of 30 µm p-p for stationary parts. Current ISO 10816-5 action limits of 30 µm p-p is more severe for the majority of large-scale turbines than the future recommended limits that will be expressed in mm/s.
- More in depth analysis of the physical relationships identified in this report

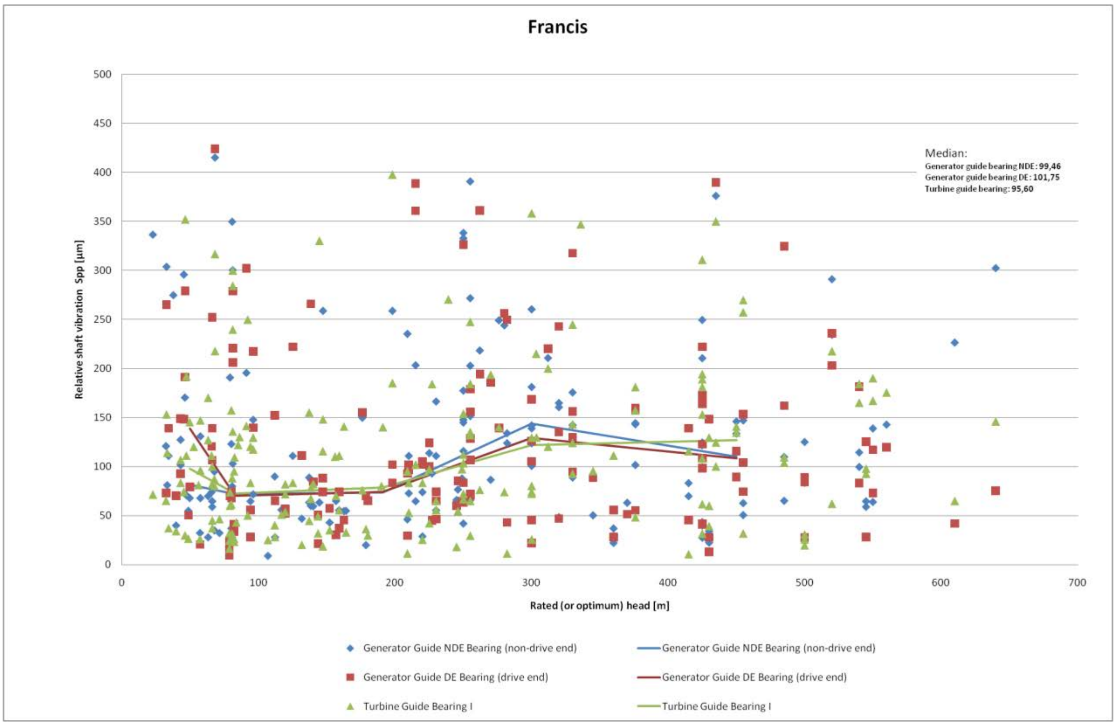
6 References

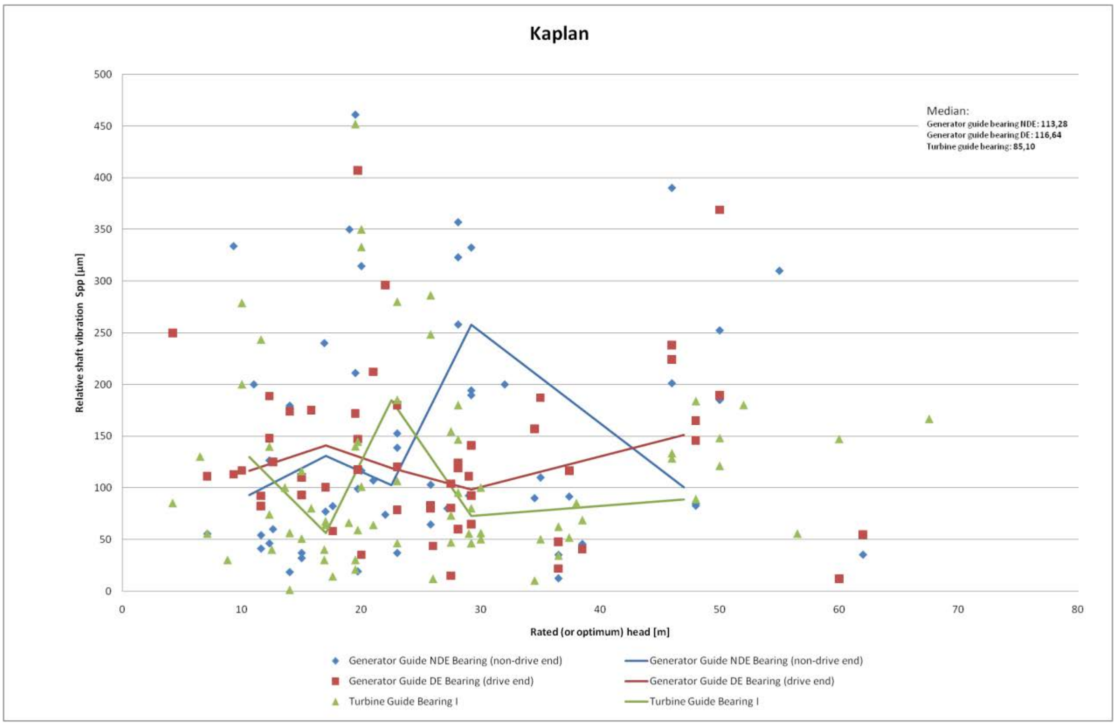
[1] M. Nässelqvist, "Simulation and characterization of rotordynamic properties for vertical machines", Doctoral thesis, Luleå University of Technology, ISSN: 1402-1544;2012:1402-1544; 2012

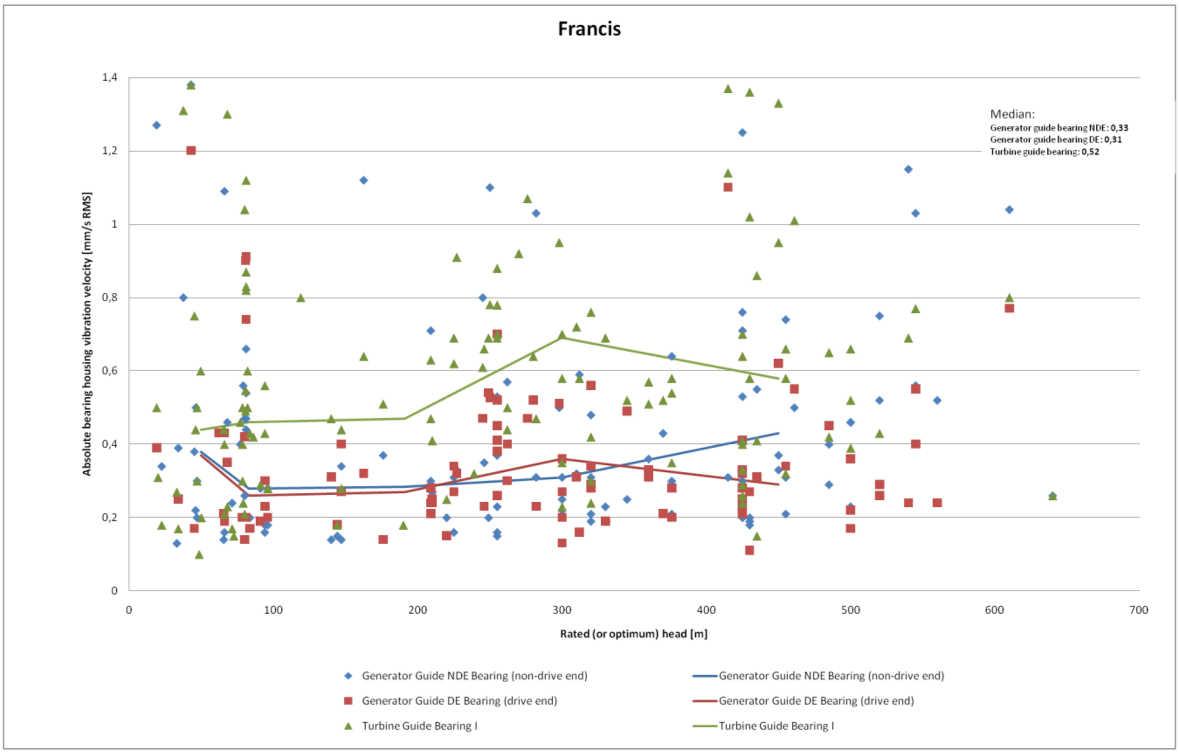
[2] IEEE Standard for Hydraulic Turbine and Generator Integrally Forged Shaft Couplings and Shaft Runout Tolerances, IEEE Power Engineering Society, Reaffirmed 14 May 2001

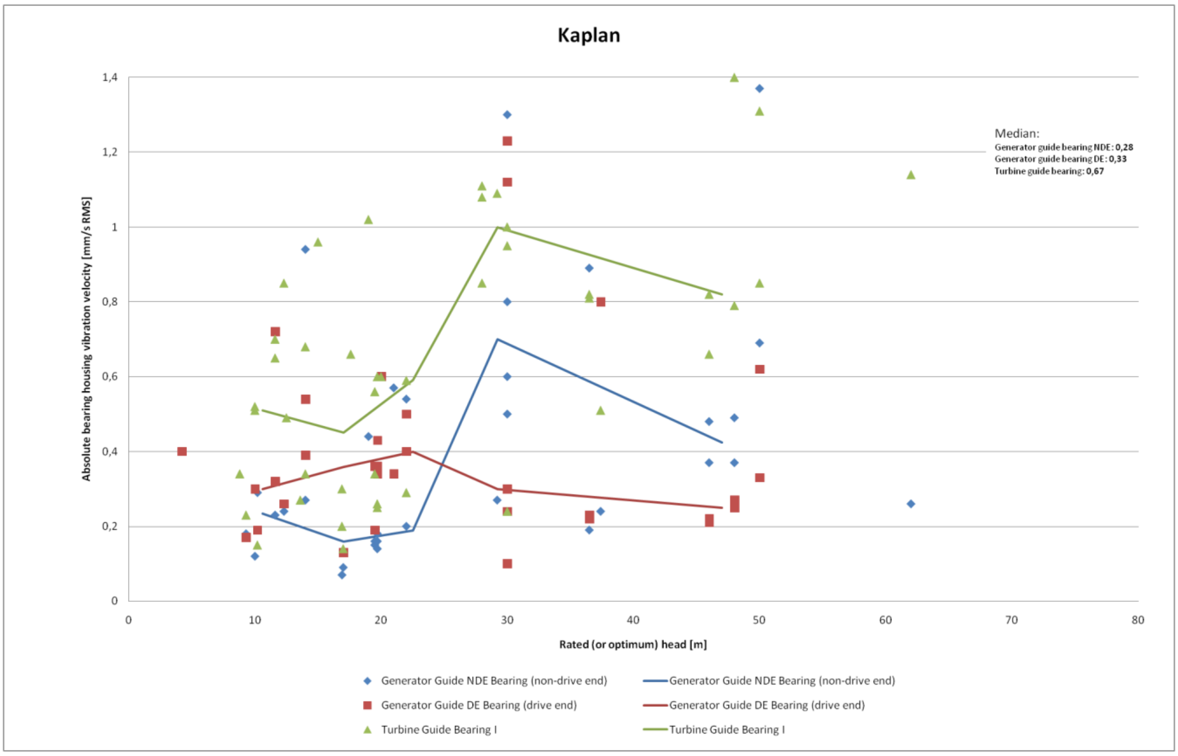
7 Appendix

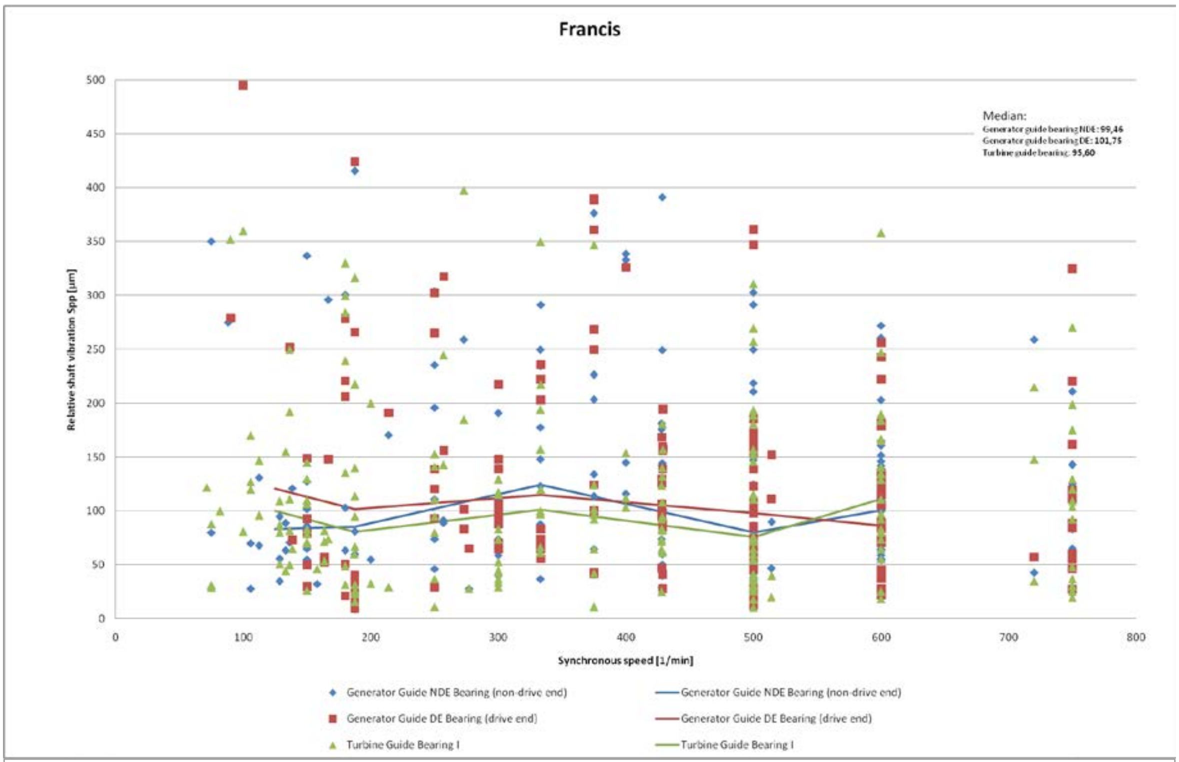
7.1 APPENDIX 1

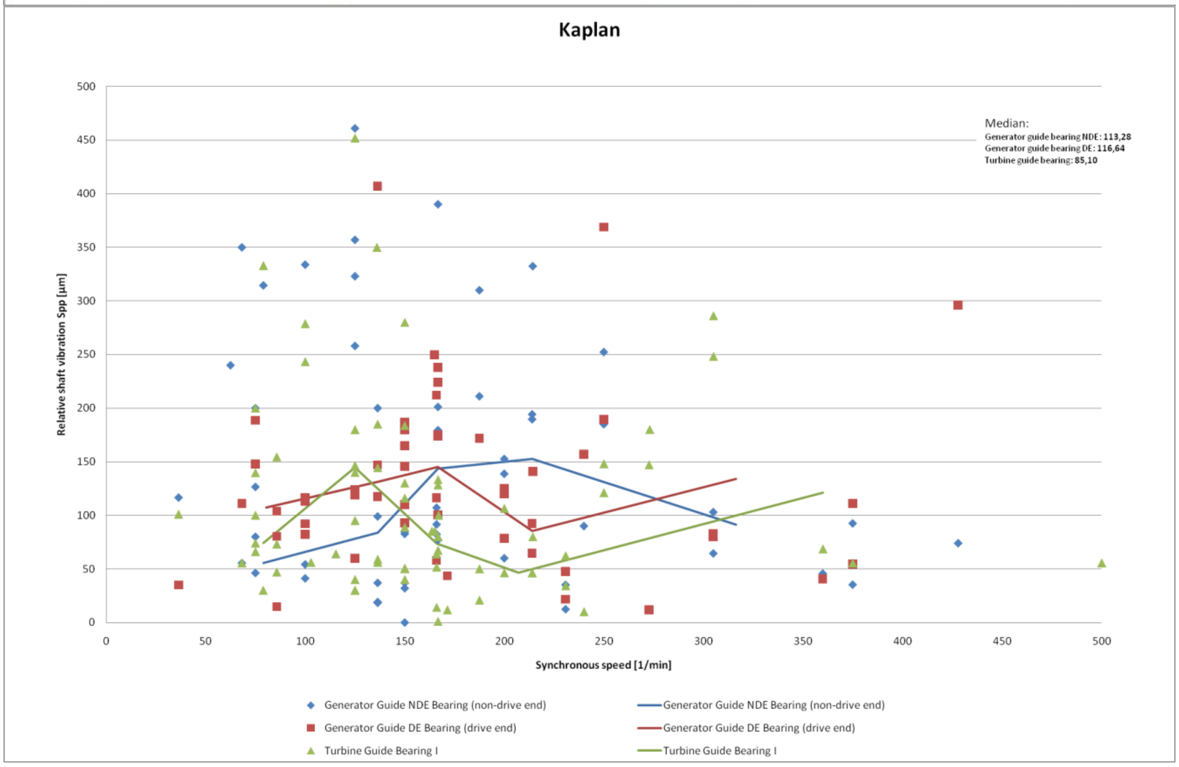


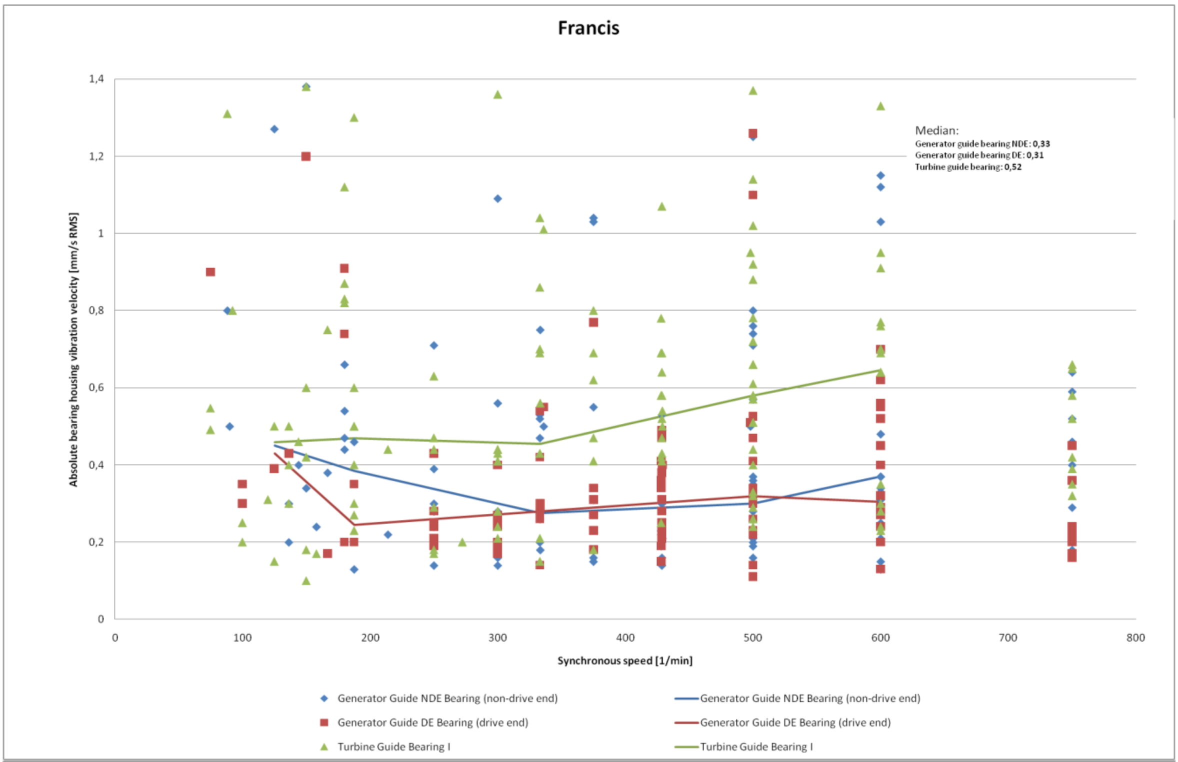


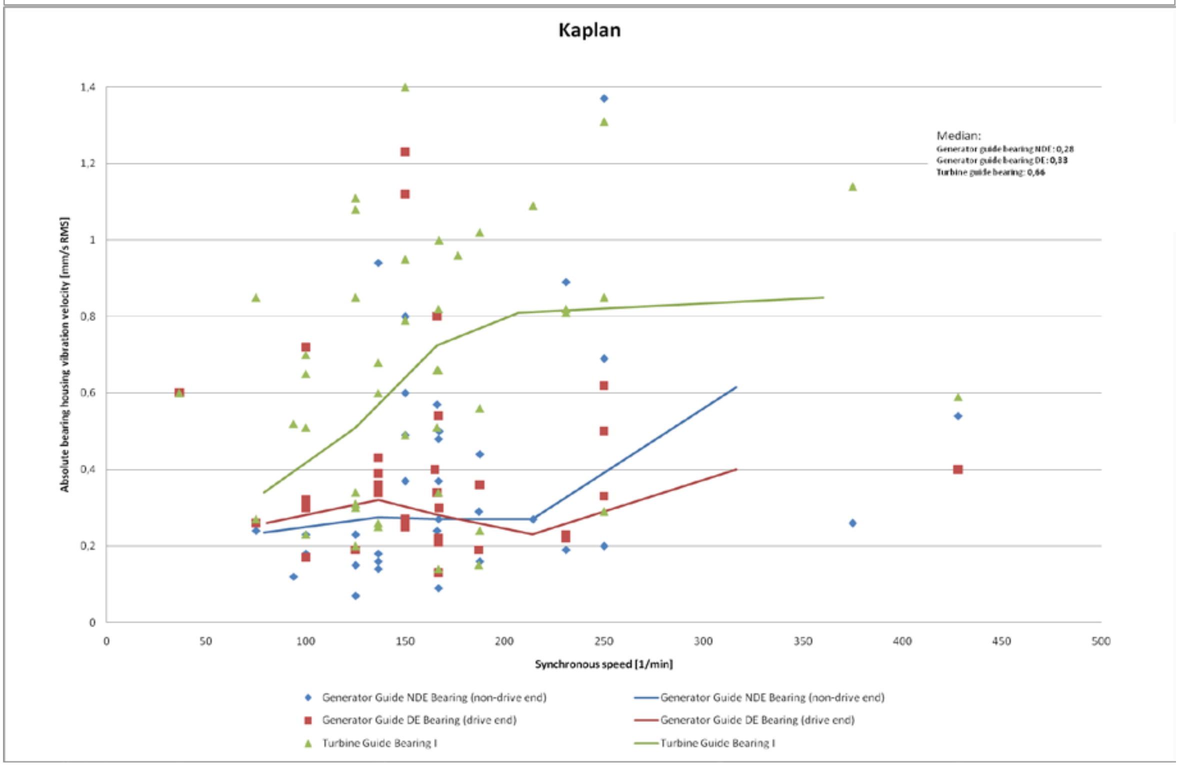

Francis
1,4
1,2
1
0,8
0,6
0,4
0,2
0
Absolute bearing housing vibration velocity [mm/s RMS]
0
100
200
300
400
500
600
700
Rated (or optimum) head [m]
Median:
Generator guide bearing NDE: 0,33
Generator guide bearing DE: 0,31
Turbine guide bearing: 0,52
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I


Kaplan
1,4
1,2
1
0,8
0,6
0,4
0,2
0
Absolute bearing housing vibration velocity [mm/s RMS]
0
10
20
30
40
50
60
70
80
Rated (or optimum) head [m]
Median:
Generator guide bearing NDE: 0,28
Generator guide bearing DE: 0,33
Turbine guide bearing: 0,67
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I


Francis
Median:
Generator guide bearing NDE: 99,46
Generator guide bearing DE: 101,75
Turbine guide bearing: 95,60
Relative shaft vibration Spp [µm]
0
50
100
150
200
250
300
350
400
450
500
0
100
200
300
400
500
600
700
800
Synchronous speed [1/min]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I


Kaplan
Median:
Generator guide bearing NDE: 113,28
Generator guide bearing DE: 116,64
Turbine guide bearing: 85,10
Relative shaft vibration Spp [µm]
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250
300
350
400
450
500
Synchronous speed [1/min]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I


Francis
Median:
Generator guide bearing NDE: 0,33
Generator guide bearing DE: 0,31
Turbine guide bearing: 0,52
Absolute bearing housing vibration velocity [mm/s RMS]
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0
100
200
300
400
500
600
700
800
Synchronous speed [1/min]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I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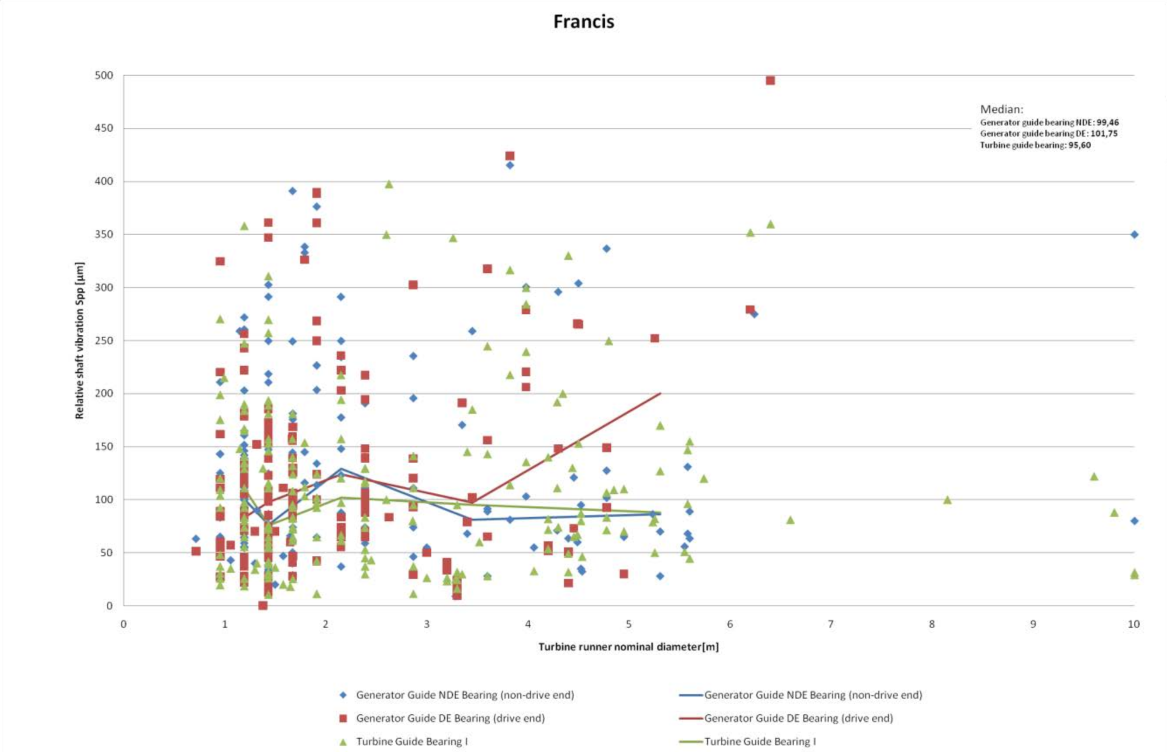
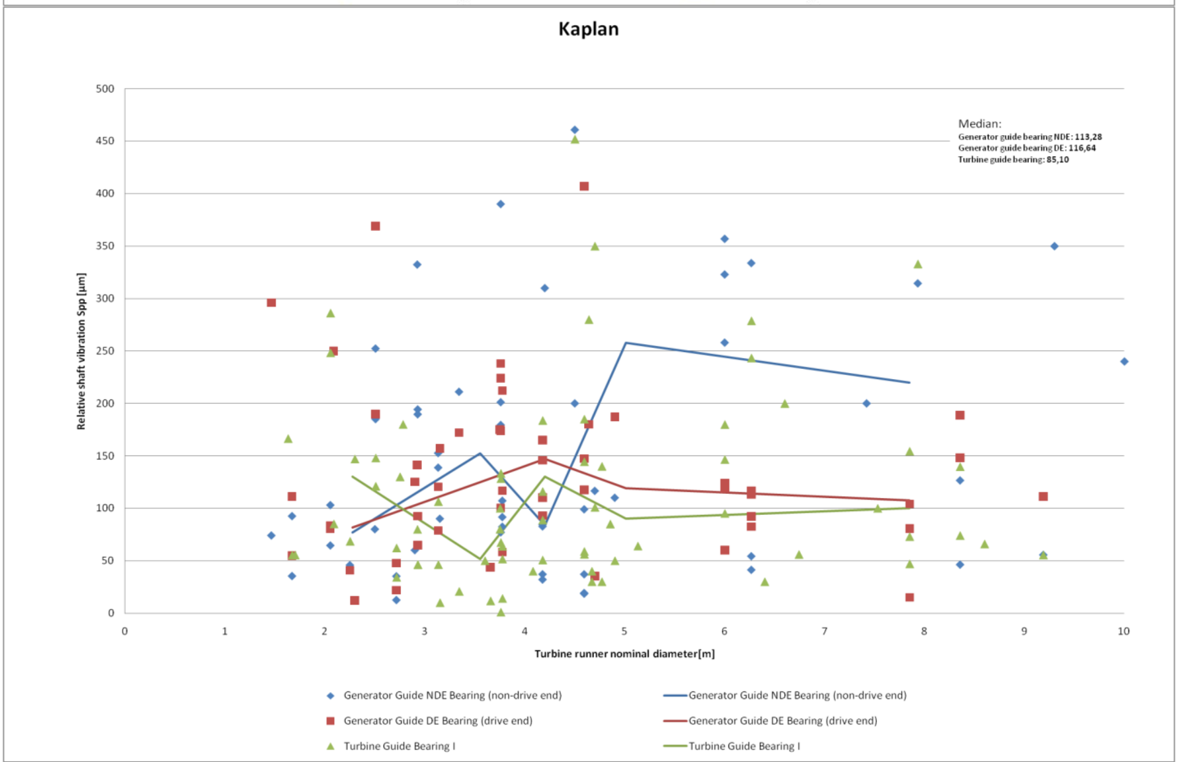
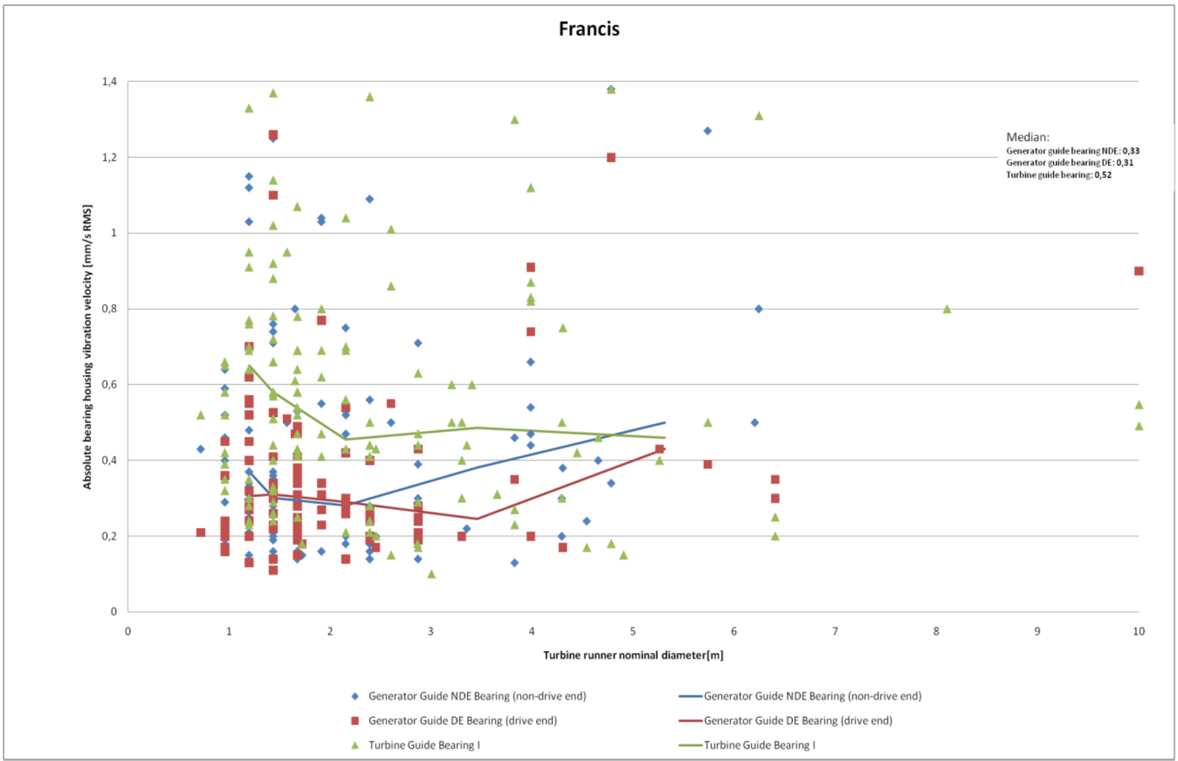
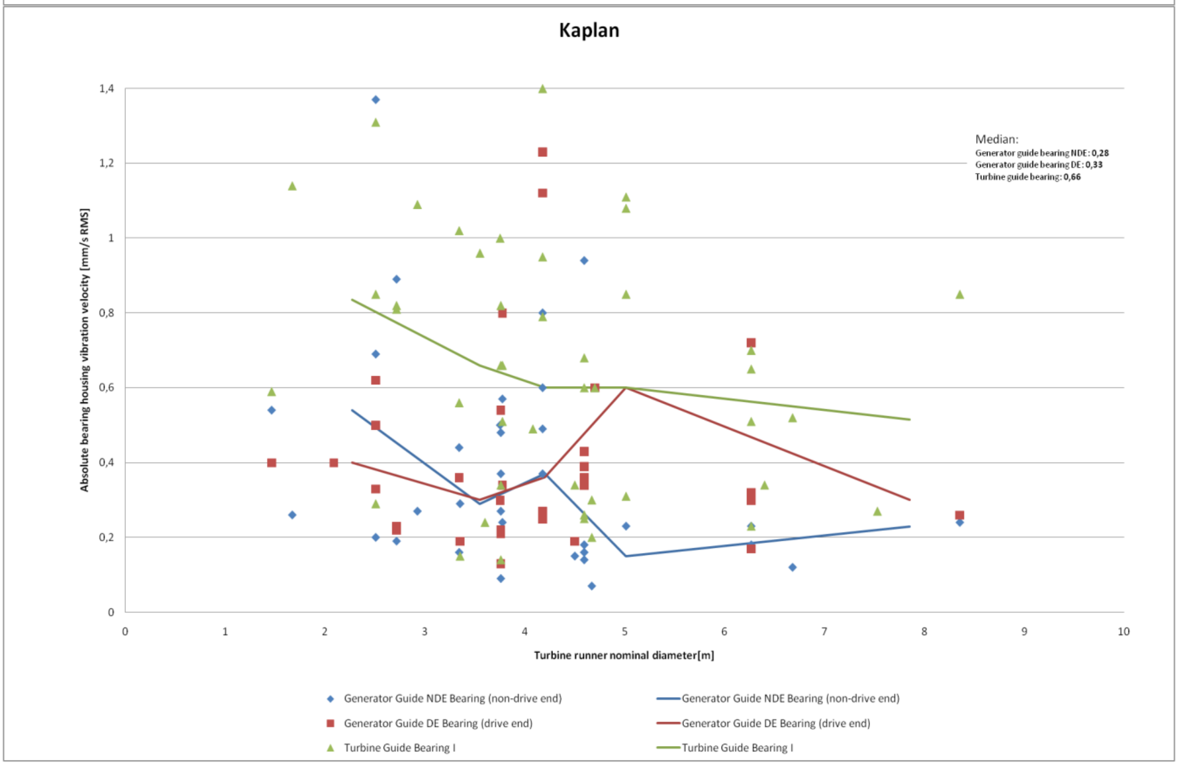
Median:
Generator guide bearing NDE: 0,28
Generator guide bearing DE: 0,33
Turbine guide bearing: 0,66
Absolute bearing housing vibration velocity [mm/s RMS]
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0
50
100
150
200
250
300
350
400
450
500
Synchronous speed [1/min]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I


Francis
Median:
Generator guide bearing NDE: 99,46
Generator guide bearing DE: 101,75
Turbine guide bearing: 95,60
Relative shaft vibration Spp [µm]
Turbine runner nominal diameter[m]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I


Kaplan
Median:
Generator guide bearing NDE: 113,28
Generator guide bearing DE: 116,64
Turbine guide bearing: 85,10
Relative shaft vibration Spp [µm]
Turbine runner nominal diameter[m]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I


Francis
Median:
Generator guide bearing NDE: 0,33
Generator guide bearing DE: 0,31
Turbine guide bearing: 0,52
Absolute bearing housing vibration velocity [mm/s RMS]
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0
1
2
3
4
5
6
7
8
9
10
Turbine runner nominal diameter[m]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I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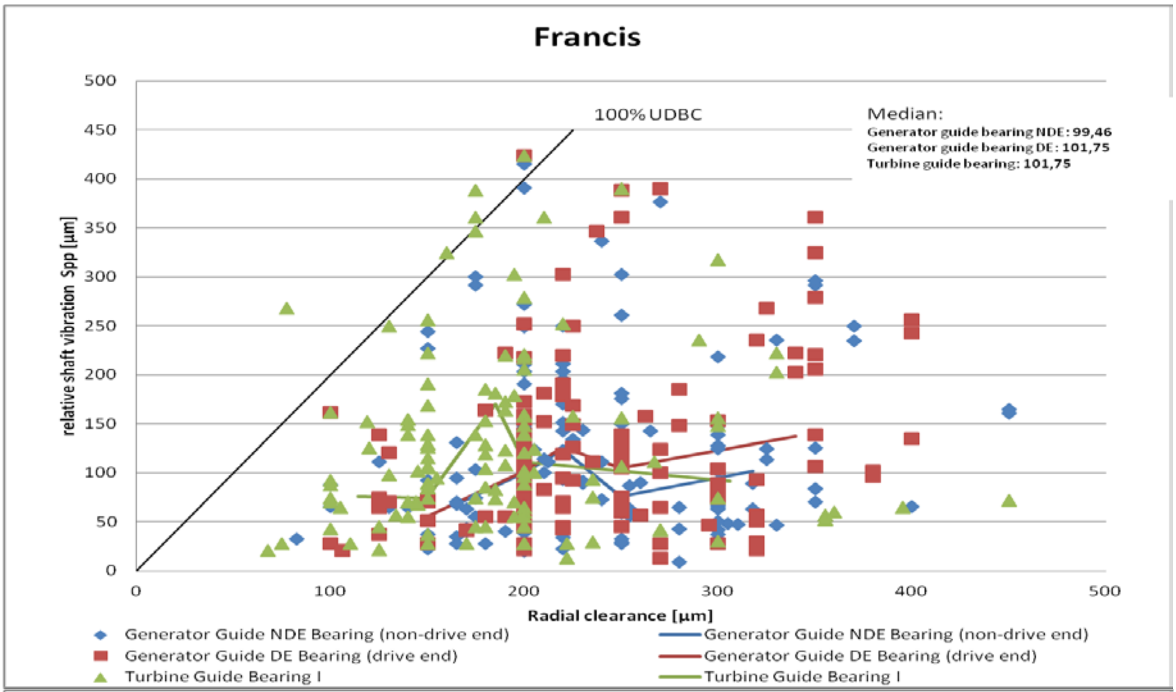
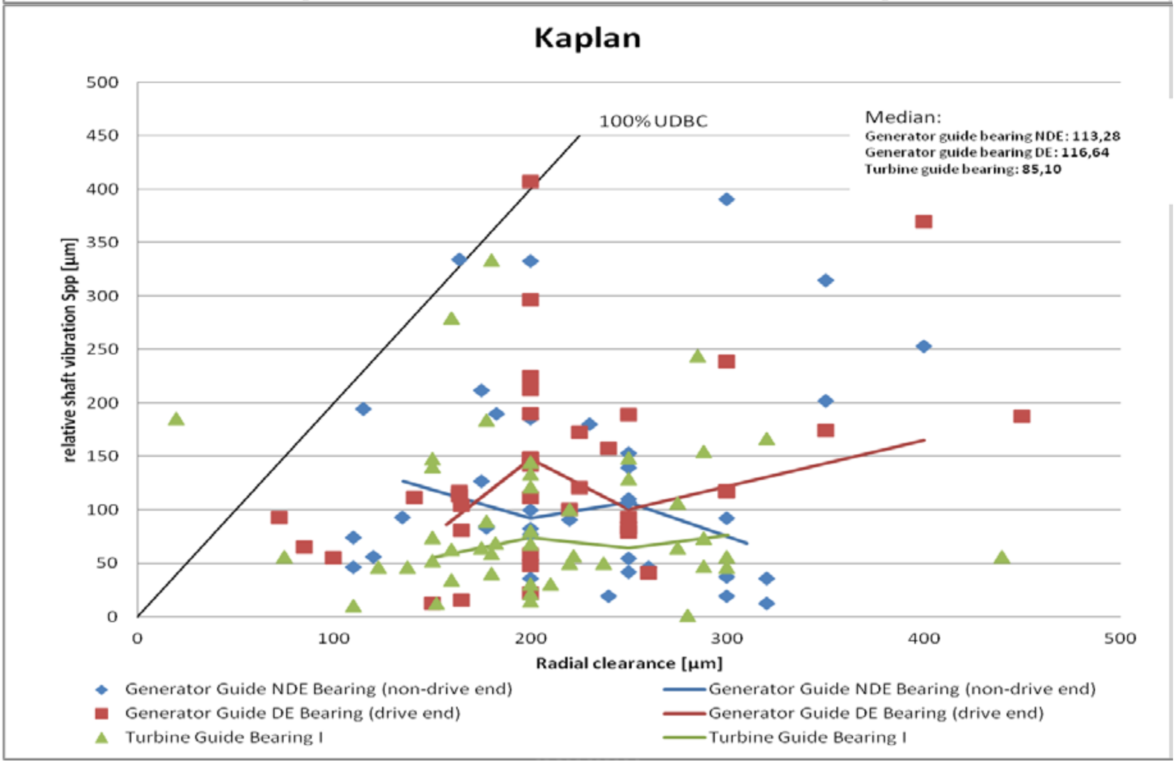
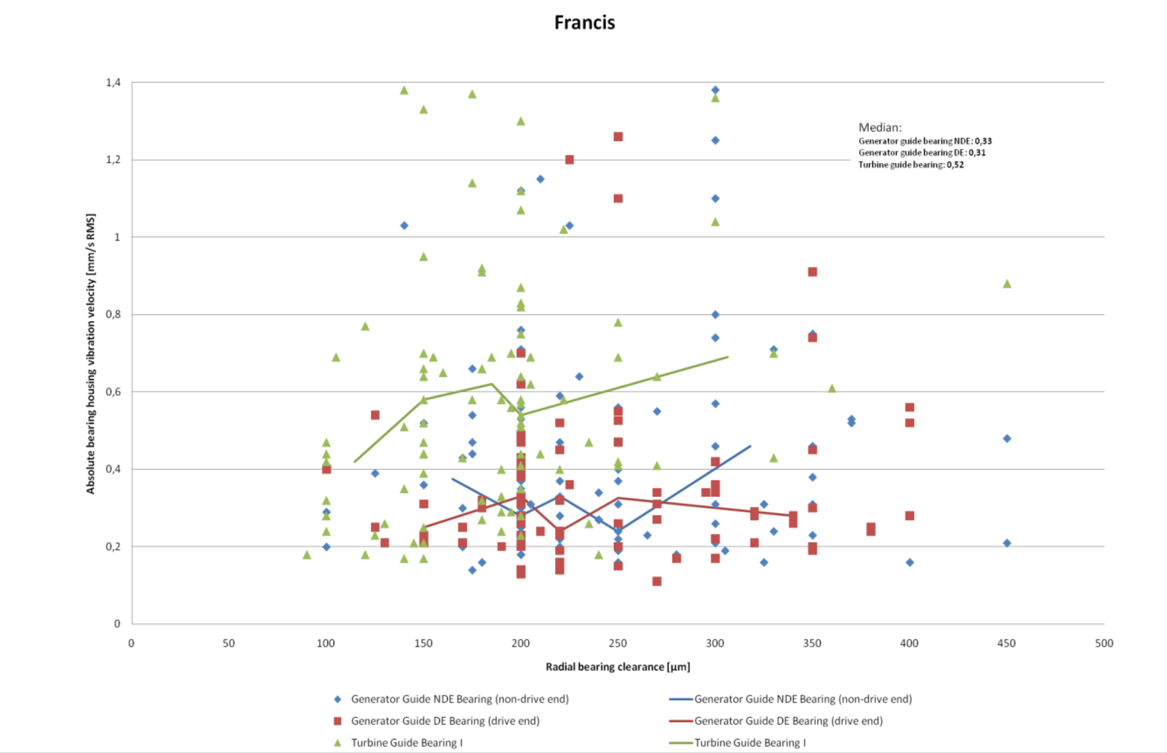
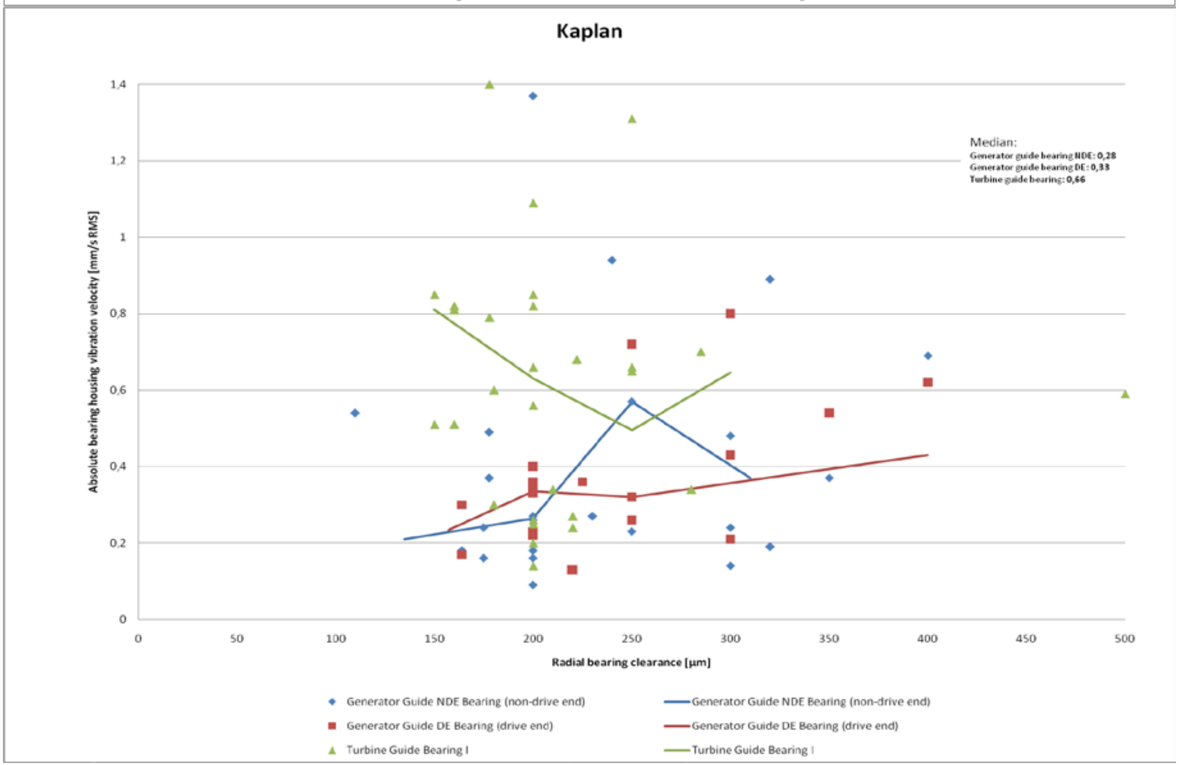
Median:
Generator guide bearing NDE: 0,28
Generator guide bearing DE: 0,33
Turbine guide bearing: 0,66
Absolute bearing housing vibration velocity [mm/s RMS]
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0
1
2
3
4
5
6
7
8
9
10
Turbine runner nominal diameter[m]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I

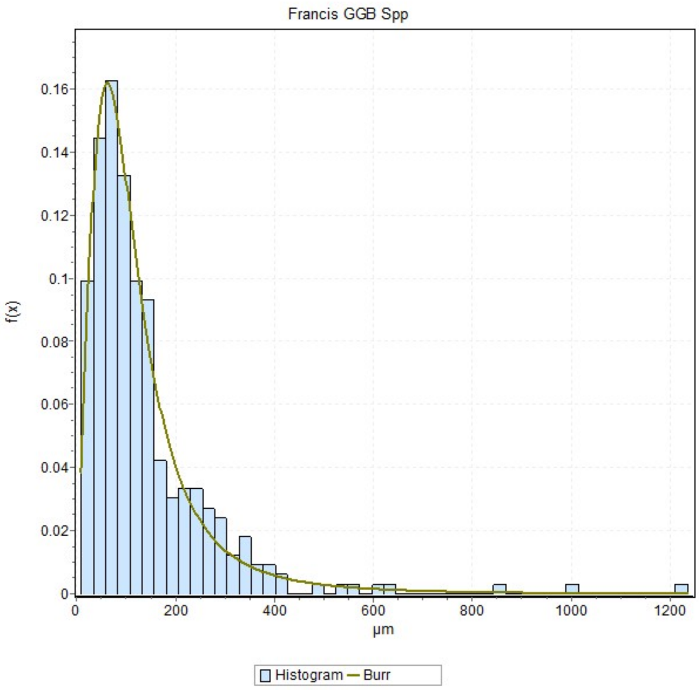

Francis
100% UDBC
Median:
Generator guide bearing NDE: 99,46
Generator guide bearing DE: 101,75
Turbine guide bearing: 101,75
relative shaft vibration Spp [µm]
Radial clearance [µm]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I

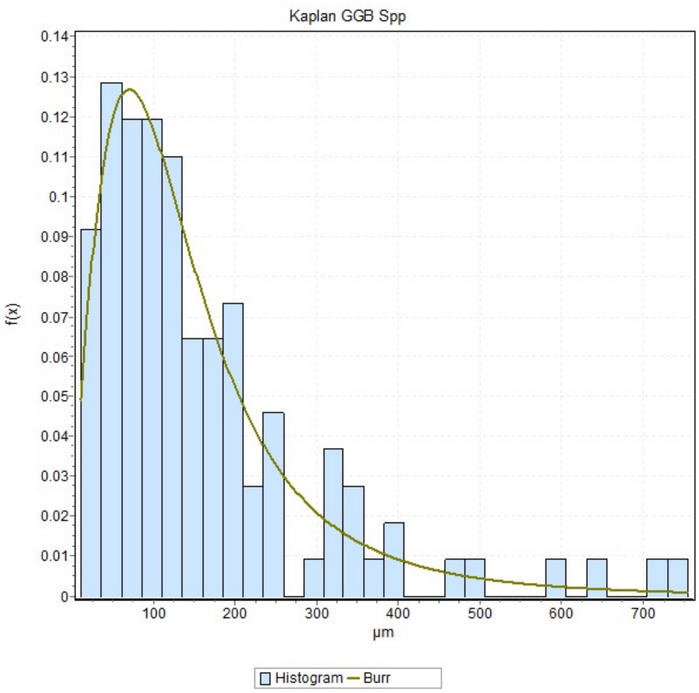

Kaplan
100% UDBC
Median:
Generator guide bearing NDE: 113,28
Generator guide bearing DE: 116,64
Turbine guide bearing: 85,10
relative shaft vibration Spp [µm]
Radial clearance [µm]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I

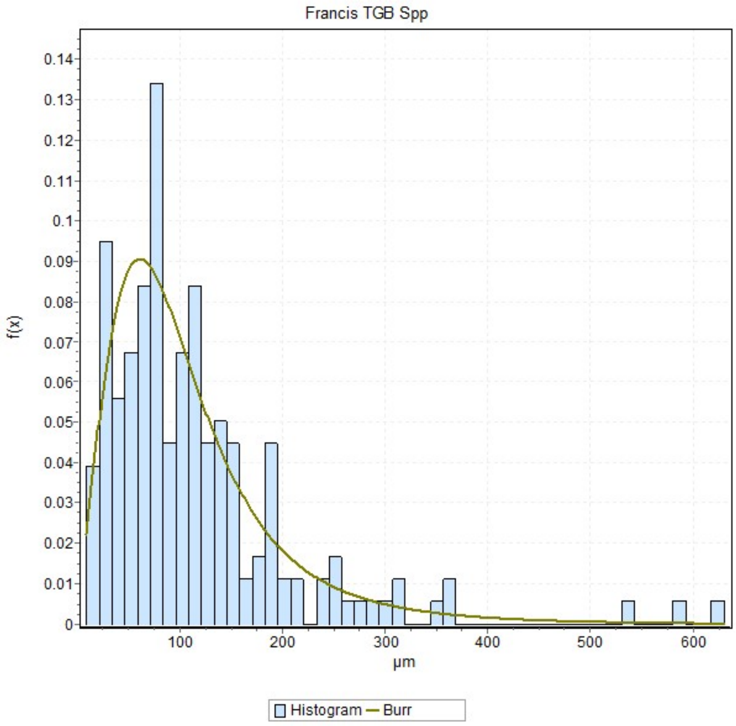

Francis
Median:
Generator guide bearing NDE: 0,33
Generator guide bearing DE: 0,31
Turbine guide bearing: 0,52
Absolute bearing housing vibration velocity [mm/s RMS]
0
0,2
0,4
0,6
0,8
1
1,2
1,4
0
50
100
150
200
250
300
350
400
450
500
Radial bearing clearance [µm]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I

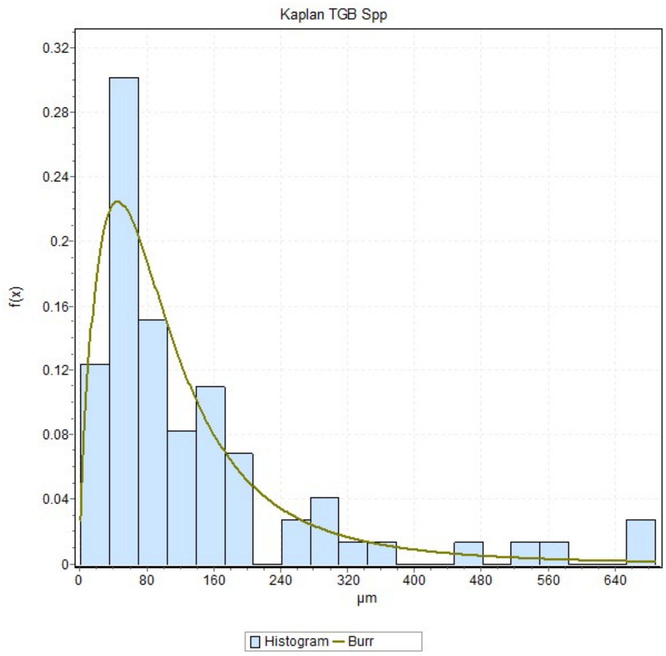

Kaplan
Median:
Generator guide bearing NDE: 0,28
Generator guide bearing DE: 0,33
Turbine guide bearing: 0,66
Absolute bearing housing vibration velocity [mm/s RMS]
0
0,2
0,4
0,6
0,8
1
1,2
1,4
0
50
100
150
200
250
300
350
400
450
500
Radial bearing clearance [µm]
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I
Generator Guide NDE Bearing (non-drive end)
Generator Guide DE Bearing (drive end)
Turbine Guide Bearing I

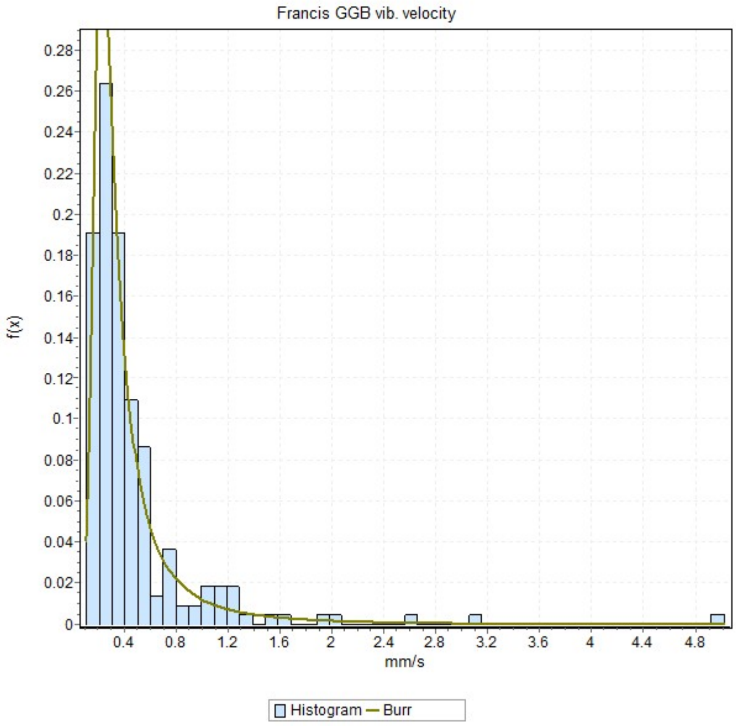
7.2 APPENDIX 2

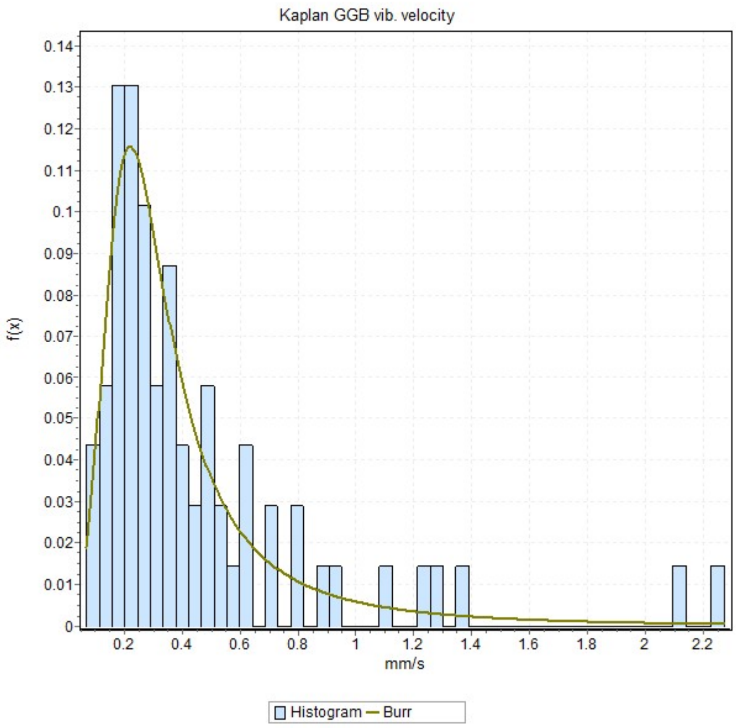


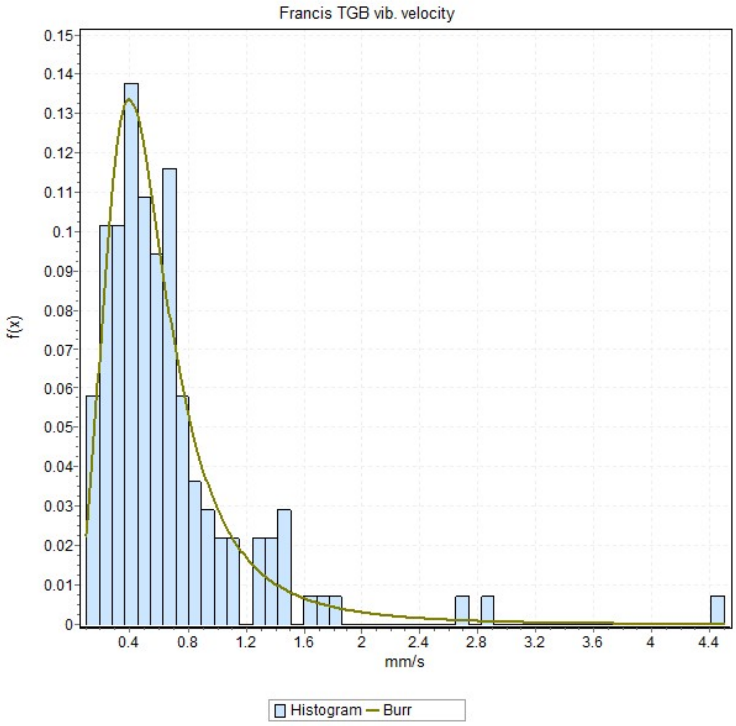


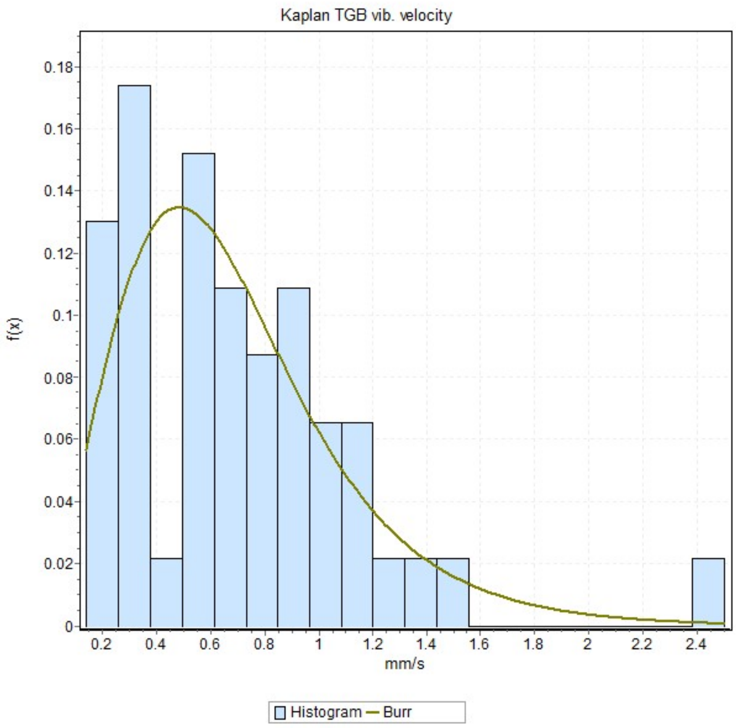

Francis TGB Spp
f(x)
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
100
200
300
400
500
600
µm
Histogram
Burr


Kaplan TGB Spp
f(x)
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0
0
80
160
240
320
400
480
560
640
µm
Histogram
Burr


Francis GGB vib. velocity
f(x)
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.4
4.8
mm/s
Histogram
Burr


Kaplan GGB vib. velocity
f(x)
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
mm/s
Histogram
Burr


Francis TGB vib. velocity
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
f(x)
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.4
mm/s
Histogram
Burr


Kaplan TGB vib. velocity
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
f(x)
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
mm/s
Histogram
Burr

Mechanical vibrations in hydraulic machines

This report is an updated version of chapter 6 in the previously published Elforsk report 12:70.

For the revision and integration of the current mechanical vibration standards for hydraulic power generating and pumping plants ISO/IEC 7919-5 and 10816-5 IEC and ISO are supporting an international workgroup (ISO/TC 108/SC 2 & IEC/TC 4 - JWG1 Vibration of Hydraulic Machines). To support the working group, analysis of the IEC TK4 vibration database has been performed by a Swedish national workgroup. The purpose of the analysis has been to form a statistical foundation for a recommendation on vibration limits in a new integrated vibration standard.

Reference values are suggested to be based on median values from the database. Actions are suggested to be undertaken if the actual vibration value exceeds 1.6 and 2.5 times the reference value.

Another step forward in Swedish energy research

Energiforsk – Swedish Energy Research Centre is a research and knowledge based organization that brings together large parts of Swedish research and development on energy. The goal is to increase the efficiency and implementation of scientific results to meet future challenges in the energy sector. We work in a number of research areas such as hydropower, energy gases and liquid automotive fuels, fuel based combined heat and power generation, and energy management in the forest industry. Our mission also includes the generation of knowledge about resource-efficient sourcing of energy in an overall perspective, via its transformation and transmission to its end-use. Read more: www.energiforsk.se

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